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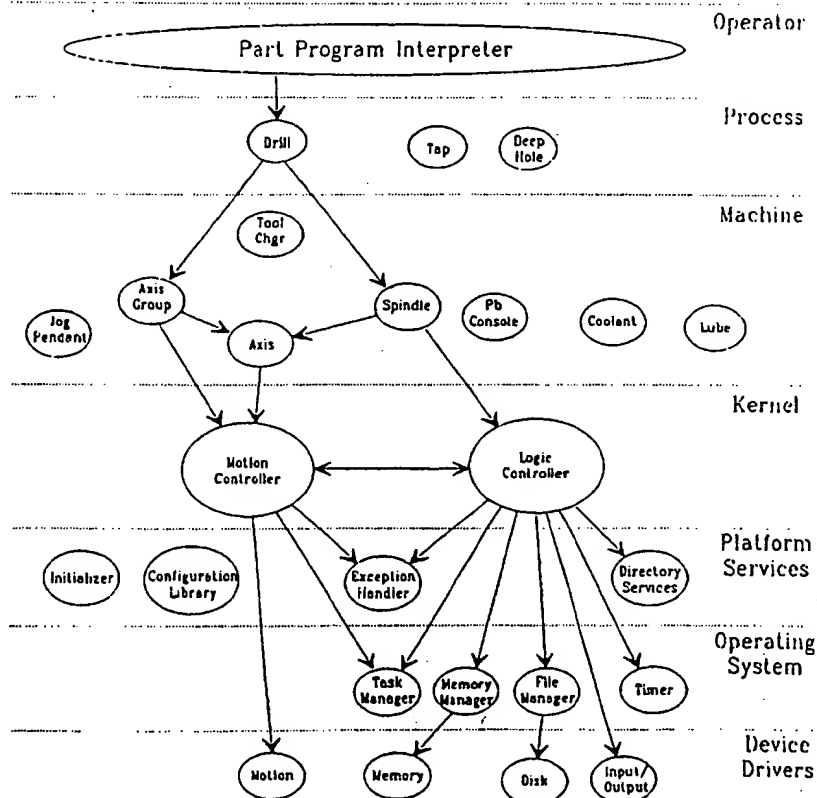
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(57) Abstract

A machine tool control system that includes a controllable, movable tool for shaping a workpiece, a mechanism for receiving control instructions describing shaping functions to be performed on the workpiece, a processing unit and memory. The control system includes objects defined according to an object oriented design. One type of object is a model of a shaping process to be performed on a workpiece, including informational parameters regarding the physical dimensions of the shape resulting from the process. The process objects communicate through an object oriented messaging system to machine objects, which represent physical devices present on the CNC machine on which the control system operates. The system also includes object oriented motion control and exception handler objects, each of which may communicate with other object via object oriented messages. The control system permits easy modifications to the control system by persons with limited knowledge about the entire control system, and is readily adaptable to advances in new CNC machine tools.



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CNC CONTROL SYSTEMField of the Invention

This invention relates to computer numeric controlled (CNC) machine tools, and in particular, to the control systems used to operate such machine tools.

Background of the Invention

CNC Control Systems The purpose of a CNC machine is to use a set of input specifications describing a physical object to produce a machined part according to the specifications. The part is typically formed from solid block stock material such as metal, and shaped by various machine tools such as drills, mills, lathes, electrostatic discharge machines (EDMs), gauging systems and the like. CNC machines are complex and include hundreds of components. Examples of input devices include keyboards, operator consoles, pressure sensitive CRTs, various tools and machine sensors, limit switches and network interfaces. Output devices include motion controllers that send motion control signals to motors driving axes or a tool, CRT displays, console status lights and audible alarms. Other components include microprocessors, memory, disk drives, data buses and wiring harnesses. The software executed by the computer processor is a critical component of a CNC machine, as it coordinates the functions of the all the other components of the system. In general, CNC software is custom written for the particular brand of components a CNC manufacturer or system integrator chooses to include in the CNC machine. As a result, CNC software is extremely complex, and a software programmer for a particular CNC machine must be intimately familiar with the way virtually every hardware component interfaces with the software, and with the entire software system itself.

For example, two representative functions of most CNC software are the logic and motion control functions (collectively referred to herein as the "kernel"). The logic control function keeps track of the specific

sequence of steps that must be taken by various movable hardware components to accomplish a task. For example, the steps required to mount a differently sized drill bit into the tool holder of a spindle from an automatic tool changer in a milling application might be: (1) send a command to raise the spindle containing the currently mounted drill bit so the tool changer will fit underneath it, (2) send a command to the tool changer instructing it to move below the spindle, (3) send a command to the spindle instructing it to release the currently mounted drill bit, (4) wait for a signal from the spindle indicating that the drill bit has been released, (5) send a command to the tool changer instructing it to move to rotate clockwise 30 degrees to position the new drill bit below the spindle, (6) interrogate the tool changer to confirm that the tool changer has successfully executed the rotation command, (7) send a command to the spindle commanding it to engage the new drill bit underneath it in the tool changer, and (8) send a command to the tool changer instructing it move away from the spindle and work area. Given the hundreds of moving, controllable parts in a CNC machine tool, the logic control function is much more complex than the above simplified example illustrates.

25 The motion control function of the software receives commands describing how a particular axis or motor should be moved. For example, in the above example for logic control, the logic control function sent the motion control function a command to raise the spindle. The motion control function takes this "general" command, breaks it down into smaller, discrete movements (i.e. controllably move the spindle up 0.001" at a time until it has moved up a total of 6 inches), and sends and receive electric signals from precision motors to ensure the movement is carried out. The motion control function is also able to execute more complex, multi-dimensional commands, such as to move the axes of a milling machine in

a pattern so as to cut an ellipse of specified dimensions in a workpiece.

Because the motion control function is the portion of the software (except for device drivers) that interacts most closely with the hardware components that actually carry out shaping processes on a workpiece, the motion control function also receives information about hardware faults from hardware devices. For example, if a hardware device is unable to execute an instruction, the motion control function will receive a notice of the error from the hardware (or its associated device driver). This information needs to be communicated back to the other portion of the CNC control software responsible for requesting the motion control function to complete the function the software is currently undertaking, so that appropriate action, such as displaying a message on the operator CRT, may occur. However, there are usually many other portions of the CNC control system software that will also need to be informed of the hardware fault. Moreover, the portions that need to know about the fault will vary depending on the exact fault. In past systems, the motion control function has been used to keep track of which portions of the CNC control system software must be notified of which hardware faults. This not only places an increased burden on the motion control portion of the CNC control system software, but also makes this portion more difficult to maintain.

Computer programmers writing CNC software have generally designed the entire software system using structured techniques that analyze what the entire CNC machine tool must do (functional decomposition). This has resulted in complex, difficult-to-modify software systems. For example, software code relating to the user interface by which a user describes a part to be machined, can be found in other portions of the CNC control system software, such as the motion controller. One example is that when a motion controller receives a signal from a

machine tool indicating a fault condition (for example, when an object in the work area prevents the table from moving to a desired location, or a blown fuse), the motion controller might directly display an error message on the CRT display. Because prior CNC control system software generally is not broken down into portions corresponding to the discrete, physical components of a CNC machine tool, a change in one portion of the software is difficult to make and frequently requires changes to other portions of the software.

Another example illustrating this problem occurs when a user, system integrator or even machine tool manufacturer wishes to add a new hardware component to the machine tool. For example, it may be desirable to replace an AC induction motor with a DC brushless motor from a different manufacturer. The new motor will likely use a different communications protocol and have different tolerance specifications and operating limits. Therefore, the motion control software will need to be modified to be able to communicate with the new motor using its communications protocol. The user interface will also need to be modified so that the user may specify the improved tolerance parameters. However, with past CNC software, these changes will have a ripple effect throughout the entire software system, greatly increasing the time required to develop a new software system capable of using the new motor. Many of the additional revisions are caused by the fact that the data the software needs to access is dispersed throughout the entire software system. For example, to add a new software function, the software may need to know, what tool is presently in the spindle, the speed the spindle is rotating, the coordinates of the axes (location of the table), the readings of a thermal sensor, information about forces being exerted on the cutting spindle, and the stage (or step) of processing the workpiece is currently in. In past CNC systems, this information would likely be diffused throughout various

software modules, and the way these data elements interact is either too complex to discern (except to the original software author), or proprietary.

These problems with CNC control systems have led to several other problems throughout the industry. There is a long lead time for system integrators or CNC machine tool manufacturers to be able to incorporate new hardware components into existing systems. This problem applies not only to new CNC machine designs, but also to efforts to add improved or additional components to an existing CNC machine tool, or to retrofit an existing machine tool with CNC capabilities. Another problem is that of scalability. Because CNC control software is usually written for use in accordance with an anticipated collection of hardware components, the same software can not be easily adapted for use in connection with other hardware components. In other words, CNC software is generally not "scalable," meaning that the software used to operate sophisticated, high-end CNC machines can not also be used to operate "bare-bones," low-end CNC machine tools. As a result, CNC manufacturers "reinvent" software having the same functionality merely because it designed to work in a CNC having different hardware components.

Programmers for CNC control systems can also be required to "reinvent" software components not just in response to new hardware, but also in response to new standards for inputting descriptions of parts to be formed by the CNC machine. The earliest CNC machines accepted part definitions through punched paper tape. Subsequent CNC machines (such as that disclosed in U.S. patent no. 4,477,754) interrogated a machine operator through a series of questions to obtain instructions about how to create a desired part. More recently, several standard data file formats have emerged for describing parts to be machined, such as the HURCO conversational or RS-274D M&G code programs. In the past "part program interpreter" modules of CNC control system programs, each module used

for accepting a part definition in a different format, would generally have to access, as described above, various data elements and software routines diffused throughout the CNC control system software. Again, each
5 different input format has resulted in a unique part program interpreter software program, and these programs all include much common, and therefore needlessly duplicative, functionality.

Object Oriented Software Most existing programming
10 languages provide "sequential" instructions for a processor to implement. These languages have previously been used to implement CNC control systems. However, computers are often utilized for modeling systems of
15 interactive components in order to determine sequences of actions such systems would perform under various conditions. For example, a programmer may wish to program a computer to mimic the manner in which some particular digital logic network responds to a particular input stimulus. When the programmer doesn't know beforehand
20 what sequence of steps the logic network would carry out in response to the stimulus, but only knows how each individual component changes its outputs in response to a change to its inputs, the programmer often finds it difficult to utilize sequentially organized instructions
25 to program a computer to model the behavior of the system.

In contrast to sequentially organized software, "object-oriented" software is organized into "objects", each comprising a block of computer instructions describing various procedures ("methods") to be performed
30 in response to "messages" sent to the object. Such operations include, for example, the manipulation of variables and the transmission of one or more messages to other objects. Messages are sent and received between objects having certain functions and knowledge to carry
35 out processes. When one of the objects receives a message, the object carries out an operation (a message

procedure) corresponding to the message and, if necessary, returns a result of the operation. Each object has a region where internal states (instance variables) of the object itself are stored and where the other objects are not allowed to access. The objects comprise concept objects that represent concepts and instance objects that represent instances of the concept objects. The concepts are clearly separated from the instances. One feature of the object-oriented system is inheritance. With respect to a certain concept object, there is defined an upper concept object that has a concept more abstract than a concept held by the certain concept object, and the certain object can inherit the functions (message procedures) and knowledge (instance variables) of the upper concept object to utilize them. For example, a concept object "circle" may inherit functions and knowledge from its upper concept object "shape."

A programmer "programs" in an object-oriented programming language by writing individual blocks of code each of which creates an object by defining its methods. A collection of such objects adapted to communicate with one another by means of messages comprises an object-oriented program. Object-oriented computer programming facilitates the modeling of interactive systems in that each component of the system can be modeled with an object, the behavior of each component being simulated by the methods of its corresponding object, and the interactions between components being simulated by messages transmitted between objects.

An operator may stimulate a collection of interrelated objects comprising an object-oriented program by sending a message to one of the objects. A method of the object receiving the message may cause the object to respond, carrying out predetermined functions which may include sending messages to one or more other objects. The other objects may in turn carry out additional functions in response to the messages they receive,

including sending still more messages. In this manner, sequences of message and response may continue indefinitely or may come to an end when all messages have been responded to and no new messages are being sent.

5 When modeling systems utilizing an object-oriented language, a programmer need only think in terms of how each component of a modeled system responds to a stimulus and not in terms of the sequence of operations to be performed in response to some stimulus. Such sequence of
10 operations naturally flows out of the interactions between the objects in response to the stimulus and need not be preordained by the programmer.

Although object-oriented programming makes simulation of systems of interrelated components more intuitive, the
15 operation of an object-oriented program is often difficult to understand because the sequence of operations carried out by an object-oriented program is usually not immediately apparent from a software listing as in the case for sequentially organized programs. Nor is it easy
20 to determine how an object-oriented program works through observation of the readily apparent manifestations of its operation. Most of the operations carried out by a computer in response to a program are "invisible" to an observer since only a relatively few steps in a program
25 typically produce an observable computer output.

Object-oriented analysis and design methods permit reuse of system analysis and requirements from other products in the same family. Object-oriented software design means that software components are created from
30 data and functions and are organized into objects. An object is an abstraction of something in the real world, reflecting the capabilities of a system to keep information about it, interact with it, or both. It is, therefore, an encapsulation of attribute values and their
35 exclusive services. An object's attributes describe the object, but not how it works. The object's services are

instructions, programs, procedures, or actions that describe what the object will do when something happens.

As described above, objects are grouped into classes. A class includes a description of how to create new
5 objects in the class and establishes the basic variables that are common to all of its objects. New objects inherit these common characteristics from the parent class. This feature allows the software engineer to build on existing design and code by creating more specific objects from the
10 easily reused code in the general class. For example, a software engineer can use a general class of characteristics for a 'device' to create a model of a more specific device such as a spindle. Object-oriented analysis and design explicitly represent commonality in
15 the system's objects and use inheritance to identify and capitalize on commonality of attributes and services. The system may only access data through the services, if at all. Services hide an object's data and send messages to perform operations. This isolates dependency on a
20 particular data structure thus permitting new features to be added without changing the arrangement of the original objects. This structure protects the data from the damage that commonly occurs during changes in monolithic, proprietary systems.

25 Objects of the Invention

One object of the invention is to provide a CNC machine tool control system that utilizes an object oriented program in which objects exchange object oriented messages.

30 Another object of the invention is to provide a CNC machine tool control system that is scalable such that it may be used for either high end or low end CNC machine tools.

Another object of the invention is to provide a CNC
35 machine tool control that is easily modifiable, in which previously written software can be reused, and in which

new objects can be added which inherit or comprise compositions of previously defined objects.

Another object of the invention is to provide a CNC machine tool control system in which new processes may be added by a programmer without requiring the programmer to know details of how particular hardware components carry out specific workpiece shaping processes.

Brief Description of the Drawings

Fig. 1 is a schematic diagram of the hardware components of a CNC machine tool system on which the control system of the present invention may operate.

Fig. 2 is a schematic diagram of the types of software classes included in a CNC control system, and several representative types of object-oriented objects within several of these classes.

Summary of the Invention

The control system of the present invention provides a real-time CNC software system that isolates system responsibilities into classes that permit a CNC manufacturer or system integrator to manage complexity and change. The control system allows different systems to be created from the same model and future, as yet unimagined, technological advances can be incorporated without redesigning or making massive changes.

The system utilizes an object-oriented software environment. A first class of object types is provided for processes (such as drilling, reaming, milling) to be carried out by machine tool components (the Process Class). Some processes objects may inherit characteristics of other objects in the Process class. For example, a "hole" object may have characteristics such as a depth and diameter, which can be inherited by other process objects, such as a drill, ream or bore process object. A second class of object types is provided which represent instances of machine tool components, such as a table (axes), a spindle, tool changer or operator console. Again, some objects may inherit attributes of

other objects. For example, an axis group, namely an object for simultaneously controlling multiple axes to shape complex three-dimensional objects, may be inherit attributes of a single axis object. Other objects may be composite objects of other tool objects. For example a tool changer may be a composite object of a collection of different milling bits which may be held in the tool changer (in addition to having its own attributes).

Most importantly, during execution of the software component of the control system, the objects transmit messages to each other. For example a drill process object can be defined to hold all the information needed to define a drilling process, and this information may be sent in a message to an Machine Class spindle object (to move the spindle down and form the hole) and to an axis group object (to position the workpiece in the proper location). However, the portion of the software which defines the drilling process does not need to access information regarding how the actual machine tool component carries out its task, or how the motion control module controls the machine components. Therefore, in a software implementation, the same process object can be used in virtually any CNC machine, without undue regard to its manufacturer or specific hardware components. Moreover, the object oriented messages through which various objects communicate provide a standard interface for adding additional functionality to a CNC machine tool control system.

For example, the primary purpose of a user interface is to collect information about a series of machining processes to be performed. Once the basic information is collected, the user interface can execute the processes by: (1) calling a process object with data about a new process to thereby create the object; (2) repeat step (1) for each process; and (3) sequentially sending a message to each defined object telling it to execute itself. Thus, the programmer of the user interface may be

completely insulated from motion control data required for the machine tools to carry out their tasks.

Because communication between software objects is accomplished through messages, software functions can be more easily distributed among different, simultaneously executing tasks. For example, instead of a motion control module needing to keep track of which task needs information regarding a particular hardware fault, information regarding a fault may merely be sent to an exception handler object. This allows the motion control module to devote more processing time to its primary task of controlling motion, and permits all error conditions to be handled in a uniform manner. Specifically, the exception handler may keep a database of which objects have a need to know about which types of faults, and report specific faults only to those objects. Therefore, in adding a new process or machine component object to the system, modification of the motion control module can be kept to a minimum as fault conditions may be handled by the exception handler.

There are seven basic Classes of software components: Device Drivers, Operating System, Platform Services, the Kernel, Machine Class objects, Process Class objects, and the Operator Class. The Device Drivers class contains the interfaces to particular hardware such as the hard drive, floppy drive, serial and parallel ports, motion board, and I/O device. This isolates all hardware interfaces into a single class that only needs to be changed when new hardware components are added to the existing system components and need to communicate in a different manner with the system.

The Operating System class is responsible for hardware and software resource management. It manages memory, timers, and the scheduling of all processes and tasks. This class makes it possible to port a control system in accordance with the present invention system to other hardware platforms. The Platform Services class is

responsible for facilitating the execution of tasks such as error handling and communication between part program interpreters and the lower levels of the system. This class simplifies system communications and only requires
5 change if advances in computer science technology need to be incorporated because they improve the efficiency or change the management of initialization and message handling. The Kernel class handles continuous motion and discrete input/output implementation components. This
10 class forms the stable core of the CNC control system that only needs to be changed when performance scaling is required. This approach is in sharp contrast to prior CNC control systems that require system developers to change the Kernel when making changes to the Operator Class
15 objects, such as the Part Program Interpreter.

The remaining three classes (Machine, Process, and Operator) specifically tailor any system to be a machine tool CNC. The Operator and Process classes are the
"tools" used to communicate clearly to the above hardware-
20 oriented classes. The Machine class contains the objects that makes this communication understandable by the Kernel components.

The Machine class is a collection of objects that embody the abstraction of real-world components such as
25 the tool changer, spindle, or coolant. This class describes all generic categories of machine tool devices by their basic required characteristics. Operator programs usually communicate through the objects in this class to the Kernel. The Machine class turns operator
30 commands such as "change to tool #6" into a message or series of messages that can be understood by the Kernel's components. New machine tool components can be added to the Machine class and existing components can be easily modified without making changes to the Kernel.

35 The Process class holds the Process techniques (methods) that perform specific common practices on the specific type of machine (low-end milling machine, lathe,

punch press, EDM, gauging system, etc.). The objects in this class use multiple Machine Class objects and can be accessed from multiple part program interpreter (operator) programs. This class usually contains libraries of canned cycles to handle such operations as milling frames, tapping, and boring, but it also contains any subroutine that several different applications need to use. The objects provide easy accessibility to the complex CNC features.

10 The Operator Class (including the Part Program Interpreter) is an extension of the CNC operator's skills and job functions. It also holds the operator programs such as part programming and system diagnostics. This class makes use of services provided by other classes to manage control of the machinery. Using programs at this level, the operator can set the system parameters (e.g., maximum feedrate) and communicate with the machine tool while it is running a part program. Most of the changes made to a CNC will be modifications to change what the operator can do. These changes usually affect the part programming and part cutting environment and can be made at this level with any accompanying techniques changed in the Process class.

25 Engineers changing a control system of the present invention can easily make changes to the system because they do not need to be experts on the entire system to make a modification to a single component in a class. One change does not have a ripple effect of change throughout the system. Portions of the system that are most likely to change such as the user interface and device drivers are separated from the Kernel. These components are more accessible to change through PLC programs, customizations to the Machine class and addition to or modification of operator programs.

35 Users of the control system of the present invention will have a more stable design that can be tested for completeness. The system makes possible the efficient

reuse of system analysis, requirements, design, and components. The system forces system designers to consider all nearly all levels of CNC responsibilities to be handled by object-oriented software. In addition,
5 changes at the Device Driver and Operating System levels may incorporate new technologies and at the Operator and Process levels will be changed to enhance or scale down system features and functionality. The core classes, Machine and Kernel, will change infrequently due to the
10 'all purpose' nature of the objects in these two classes.

The present system uses an open systems, object-oriented design approach. This allows users to tailor hardware and software to gain the competitive edge. The CNC control system allows easy integration of hardware
15 and software from different suppliers and permits the porting of systems to other hardware platforms. Industry standard hardware interfaces to simplify assembly and maintenance may be used. The system is dynamically reconfigurable to easily permit third party development of
20 software components. The system uses simple, standard messages in a message schema. The messages are flexible and allow a user to select messages they want to use and to alter the messages to meet their needs. The system software is scalable to support less expensive and/or a
25 full-featured CNC hardware system using the same software structure.

As with data characteristics, services can also be inherited from the parent class when a new class or object is created. Of course, the new class or object may use the
30 service or create a different version of it. Different objects can use identical services. Therefore, a software engineer writes the code for the service only once and then reuses it after that. The reusability of existing object-oriented code makes development and modification
35 faster because there is less to write and maintain.

A diagram of the system of classes of software component classes is shown in Fig. 2.

The software objects use messages to communicate between the components. The class structure simplifies system operations and programming by limiting the messages of interest to each class. For example, the Machine class
5 does not worry about the Kernel's responsibilities such as travel limits and servo errors. Conversely, the Kernel is not concerned about ownership or devices because the Machine class handles that exclusively. Messages sent from the Operator and Process classes to the system
10 devices can originate from several sources, including the Part Program Interpreter, the User Interface, Push Buttons on the Console or Jog Pendant, or a Sensor Interface. Applications can communicate with the Kernel through any or all of the system classes. For specific functions, a
15 software engineer may bypass a class and connect an application directly to the next class or another class down. This is accomplished through the standard message formats supplied for each object component in the system.

The present invention is designed as a series of
20 autonomous processes rather than a monolithic piece of software which is typical of embedded software systems. As such, a reliable and predictable interface is required for inter-process communication. The details of the communication are encapsulated into an object referred to
25 as the "Transporter" or transport layer. This object is instigated by each process that intends to communicate with other processes. Communications to other processes are requested by symbolic name.

A directory of processes allows for identifying the
30 various processes by symbolic name. A continuously running process commonly accessible process referred to as "Directory Services" allows all the processes connected with the system to register their existence, symbolic name, and communications channels. Periodically,
35 Directory Services interrogates all the registered processes to determine if they are still active. If any processes is determined to be inactive, it is removed from

the directory and its communications ports closed. This commonly accessible process, having a predetermined message protocol, allows the other processes to be independently developed and maintained.

5 A message object is defined as the base class for the data to be transmitted between processes. The message object contains all of the fundamental information necessary for routing information to the other processes. Specific derivations of messages are inherited from the
10 message base class. The contents of these derived messages have commonly defined characteristics. Messages contain identifiers that inform the recipient process of the action to be carried out or the type of information being transmitted. The identifiers are designed as
15 objects so that the specific details of the ordering of data is transparent to third parties. Also, this allows for messages to be used as base classes for other message classes not yet conceived.

The messaging approach to inter-process communication
20 facilitates the independent development of processes for interconnection with the system. The Transporter uses operating system features to implement the actual message transmission. If a different operating system is used as the core of the system, the Transporter layer may easily
25 be exchanged with no impact on the rest of the software. In most conventional systems, moving a system to another computer platform creates significant modification of the system software. With the present invention's object-oriented, message passing approach, the system may
30 be more readily moved to another computer environment. This message passing approach also limits the impact of software flaw because clearly defined interfaces and formats play a significant role in building and preserving robust software.

35 The general format for messages sent between classes is set up as a data structure containing a common header and the arguments that are unique for each specific

message. The header includes several variables that are common to all messages. The messages are designed to be variable length for efficiency. The message type is a static identification number which is unique to the class of message being sent (e.g., a calibration message). The transaction number, unique for each specific message transmission, is assigned at the time the message is sent and is used to match responses to the messages.

The response message is set up so that it uses the request message's ID and transaction field, and the status is set to 'received' or 'completed' or 'denied' as required. This makes it is clear which request is associated with the response. Responses have no arguments associated with them. Anything that requires arguments to be passed is considered to be a new message. For example, the response to an IOSendNode message is an IOInfo message with the data field passed as an argument. A Sample message structure is as follows:

```
/* The message header includes information about the
message itself */
typedef struct lc_header_type
{
    int  msg_size;      /* Length of message */
    int  header_size;   /* Length of header info */
    lc_msg message;     /* The enumerated message number */
    int  transaction;   /* The message transaction number */
    enum type;          /* The type of message (request /
response):
    0 = this is a request (set by sender)
    1 = request received (set by receiver)
    2 = request completed (set by receiver)
    3 = request denied (set by receiver)
    4 = no service available (set by receiver) */
} lc_header_type;
```

There are three types of messages: actions, information blocks (info), and cycles. Actions are system messages that are required to conduct basic communication

between system components and do not change from one machine type to another. Info messages include a block of information that was either requested by a system component or that is sent relative to a button-event, key-press or mouse-click for example. Cycles are messages that perform customized operations that may change from one machine to another. Cycles may be supported by ladder logic sequences in the Logic Controller program. In addition to using new and existing Cycles, the system integrator may take advantage of the Softkey and Prompt messages in conjunction with ladder logic to form customized operations that allow interactive input from the operator console. For example, toolchanger calibration could be done by invoking a ladder logic sequence which responds to a specific softkey and then performs the logic necessary to do calibration for a particular machine. This would require no hard-coded software in the system and would be completely configurable by a system integrator without the control builder's assistance.

Any Part Program Interpreter (PPI) may be used as long as it uses the embodiment's interface.

Components of the Operator Class may include the following: Conversational part program interpreter, NC interpreter, Manual mode user interface, Auto mode user interface, Diagnostics user interface, Program editor for conversational programming and Program editor for NC programming

The Process class contains pre-packaged objects using multiple class objects. When an application uses packaged cycles, the operator can specify a type of operation and define only the necessary variable information. Then the system makes additional calculations to define the operation fully. For example, when the operator is programming a shaping process such as a hole-making drilling operation with pecking, the operator simply specifies the peck type and depth (thereby defining the X, Y and Z dimensions) and the system uses a canned cycle to

determine the exact movements of the drill during the pecking process. Another example would be a milling object which represents a milling operation to be used to shape a workpiece. The object may further include means
5 for defining whether the shape to be milled is to be removed from the workpiece or left remaining in the workpiece. The object may also include sequencing status means representative of whether the process defined by the object has been performed. In one embodiment, packaged
10 cycles are contained in libraries that can be used by different operator programs with little or no modification. These cycles are pre-programmed, common machining operations and include drill, tap, peck and ream.

15 The Machine class forms a device-oriented interface between the details of the Kernel and the operator programs and canned cycles. The Machine class manages the complexity of the system by handling the device responsibilities between the operator programs and the
20 Kernel. The Machine class establishes and monitors the operator programs' connections to the Kernel and handles messages between the applications and Kernel. Each application has a copy of the Machine class included in order to interface in a common way to the Kernel. Shared
25 data assures that all applications use the same Machine class state information.

Since the Machine class uses object-oriented design, it contains objects that define specific devices with possible functions for each device. For example, some
30 possible functions of the spindle object may be run, clamp, and stop. The object's data describe the speed range and current speed. An operator program may not necessarily use all of a Machine class object's functions, but the functions are available and supported by the
35 Kernel.

Typically, a copy of the Machine class will be attached to each operator application being used in order

to provide a common interface to the Kernel. In addition, a customer may extend the functionality of the Machine class being used, as long as the same Machine class is being used by all operator programs. One embodiment of the Machine class contains the following objects: Push-button Console, Jog Pendant, Axis, Axis Group, Spindle, Tool Changer, Coolant and Lube.

The Kernel provides mechanisms for coordinating multiple, servoed axes and to provide discrete I/O control. The CNC applications communicate with the Kernel components, the Logic Controller and the Motion Controller, through the Machine class. These Kernel components decide how to implement the operator programs' commands for the hardware provided.

The Motion Controller provides multi-axis coordination as in most commercial CNCs. In its basic form, it controls five coordinated axes plus one spindle and two auxiliary axes. In addition it supports several types of interpolation algorithms including linear, circular, elliptical, helical, and polynomial. Applications communicate with the Motion Controller through the Machine class message interface.

The Logic Controller (LC) contains two programs: programmable ladder logic and the LC engine. The LC uses a window-based programming environment either off-line or at the Operator level to simplify production of a logic program to run on the LC. The LC also has software tools to change, debug, and monitor the operation of the ladder logic.

The Platform Services class of the present invention provides the structure that allows operator programs and third-party software to connect to the system and communicate with other software applications. There are four services that control system connection and communication:

Initialization Sequence - a file, similar to a PC's autoexec.bat file, listing all operator programs in the order that they will start during start up;

Directory Services - a registry of all active programs;

Machine Configuration Library - a shared memory area to store default machine parameters for application configuration. This is similar to the win.ini file in the Microsoft Windows system; and

Exception Reporter - collects, organizes, stores and distributes all errors of interest to the active applications

Directory Services contains a 'phone book' that lists all running applications. Applications register with

Directory Services and receive addresses of the other applications with which they need to communicate.

Directory Services does not assume any specific communications connections. This means that the system is dynamically configurable to allow addition of other

applications that use the interfaces of an embodiment of the present invention. Applications store the addresses they receive from Directory Services in their own

directories. Applications, such as the Kernel, that need machine configuration parameters can retrieve those

parameters from the shared memory where the Machine Configuration Library stores the information.

An operating system usable in connection with the present invention complies with IEEE-1003.1 POSIX (a standard for application programming interface for UNIX)

and the IEEE-1003.4 POSIX standard that defines real-time extensions. This embodiment uses the Lynx operating system (LynxOS), a real-time, UNIX-like, operating system that runs on any 386 PC/AT or greater compatible computer.

LynxOS has these characteristics: (1) Compliant with POSIX

1003.1, POSIX 1003.4 real-time extensions and POSIX 1003.4a threads interface; (2) Full UNIX compatibility (binary and source with System V, source with BSD 4.3);

and (3) Completely deterministic, including Multi-tasking with user-defined priority levels, Multi-threaded support for real-time ADA, Offers demand-paged virtual memory, Runs off-the-shelf Interactive UNIX System V software without recompilation, and Networking and communication facilities including TCP/IP and NFS. The LynxOS development tools including over 170 UNIX-compatible utilities and the standard UNIX libraries may also be used. The tool set used in one embodiment supports DOS I/O facilities, Debugger software, Re-entrant device drivers, Compilers for C, FORTRAN, Pascal, BASIC, and ADA, GNU Package (GCC, Emacs, GDB, C++), X Window System, Motif, Network File Sharing (NFS) and Transmission Control Protocol/Internet Protocol (TCP/IP).

The Device Drivers class forms the interface between the operating system and the hardware devices such as I/O peripherals (e.g., serial communications ports), video displays, and mass storage devices. The operating system calls these drivers when a device is installed (at boot time or dynamically) and when application programs need to access a device. The device drivers in the embodiment are capable of handling multiple devices and respond rapidly to high-priority tasks. The present invention contains the following types of drivers: PC/AT keyboard and serial mouse, Analog input/output card, SCSI device driver, Floppy disk device driver, Ethernet interfaces, Internet message and transmission control protocol, Internet protocol and protocol family, Internet user datagram protocol, Pseudo terminal driver, Hard copy and video terminal interface, NFS client I/O and server drivers, CANbus, and MATRIX4

Detailed Description

Overview - Hardware

Fig. 1 is a schematic diagram of a typical CNC machine on which the control system of the present invention may operate. A standard PC-compatible ISA bus is connected to CPU processing unit 11 and its

associated motherboard, preferably an Intel 80486 class microprocessor. The bus may also access RAM memory 12, which may alternatively be connected directly to the motherboard. ISA bus 10 may optionally provide an
5 interface to network 13. Mass storage device 14, which may include both hard and floppy disk drives is also connected to ISA bus 10, as are standard communications ports 20, motion control board 18 (preferably a DSPCG, Inc. (Minneapolis, MN) Matrix 4 / Vector 4 combination
10 mounted on a VME bus), and video interface 15.

In one embodiment, the CNC machine specific hardware of the system are interconnected via a CANbus bus system. Accordingly, CANbus interface card 16 is also positioned in ISA bus 10. CANbus cable 17 connects other CNC machine
15 hardware components and provides communication therebetween, CNC machine operator console 19, jog pendant 21, and servo motors 25, 26. In general, motion control board 18, or CANbus interface 16 and CANbus cable 17, provide means for transmitting command signals to a
20 movable tool, such as servo motors 22-26 and/or the axes or tool fixtures connected thereto. Servo motors 22-24 control movable tools for shaping a workpiece, such as X, Y and Z axes of the machine tool, respectively, while servo motor 25 may control the spindle which rotates a
25 cutting tool. Servo motor 26 may control an tool changer which holds a plurality of workpiece shaping tools, such as milling bits or may control a rotary table.

The system uses industry standard cards including the new CANbus distributed I/O card. This bus allows a user to
30 attach nodes to the system rather than insert cards into the cabinet. The high availability of the cards keep prices low and reliability high. Standard board sizes and mounting holes keep the system open to changes and upgrades. Keyboards, trackballs, and jog pendants are
35 connected as CANbus nodes to the system. The keyboard may be located away from the main platform without decreasing the quality of the signal. However, to comply with safety

standards, the emergency stop button and the power on/off switch are wired directly.

The control system of the present invention System offers two back plane buses: ISA and VME. Both meet LynxOS and POSIX standards and communicate with the control system software. Using CANbus and MATRIX4 with either bus permits real-time path correction based on auxiliary sensors such as vision, secondary axis, and temperature sensors.

The system's I/O backbone is the CANbus, a multi-master serial bus. CANbus can be structured to form many different architectures because it has different types of PC configurations and the CANcore module to standardize the interface to I/O peripherals. CANcore acts as a CANbus node allowing the customer to connect peripheral I/O through the industry standard SPI (Serial Peripheral Interface) Bus.

The system uses the MATRIX4 to decrease system integration costs, increase motor control system performance, and create component sourcing options for the customer. This controller is a fully digital, 4-axis position controller available on both the ISA and VME host platforms. The flexibility of the controller design allows a user to adapt the controller to any motor design on the market. The controller is capable of interfacing to DC brush, DC brushless, and AC induction motors and allows most parameters to be programmed dynamically. This allows immediate updates when there are changes in the environment or operating conditions.

Overview - Object Oriented Systems

An overview of the broad categories of the software components of the CNC machine control system of the invention is shown in Fig. 2. In the Operator class are software programs generally classified as the Part Program Interpreter (PPI) or user interface. This type of software is generally well-known in the art, and except for the way it communicates the information it obtains to

the remaining software components, does form a part of the invention per se. The PPI may either interrogate the operator to input steps to machine a workpiece, or may prompt the user to specify a data file having a digitally
5 stored part manufacturing description. Regardless, once information about the part is obtained, the PPI dynamically creates appropriate objects in the Process class as further described below.

The control system of the present invention uses
10 object-oriented design and programming object-oriented design means that software components are created from data and functions and are organized into objects. Software components communicate through messages sent between objects. Objects have two parts: data and
15 methods. Objects are abstract representations of the basic things a system handles (e.g., a spindle, tool changer, or type of motion). An object's attributes describe the object, but not how it works. The object's methods, are instructions, programs, procedures, or
20 actions that describe what the object will do when something happens. So a spindle object's methods may be initialize, run, orient, speed override, and stop. The object's data describe the speed range and current speed.

Using object-oriented programming, objects can be
25 quickly created using a class, the blueprint for the objects. The class establishes the basic variables that are common to all of its objects, and the new objects inherit these common characteristics from the parent class. This feature allows the software engineer to build
30 on existing design and code by creating more specific objects from the easily reused code in the general class. For example, a software engineer can use a general class of characteristics for a 'device' to create a model of a more specific device such as a spindle.

35 A method belongs to an object and indicates how to perform an action or how to react when an action is performed on the object. The system may only access data

through the methods, if at all. Methods, therefore, hide an object's data and send messages to perform operations. This isolates dependency on a particular data structure thus permitting new features to be added without changing the arrangement of the original objects. This structure protects the data from the damage that commonly occurs during changes in monolithic, proprietary systems.

As with data characteristics, methods can also be inherited from the parent class when a new class or object is created. Of course, the new class or object may use the method or create a different version of it. Different objects can use identical methods. Therefore, a software engineer writes the code for the method only once and then reuses it after that. The reusability of existing object-oriented code makes development and modification faster because there is less to write and maintain. An additional benefit of using object-oriented methods is the localization of change. Data hiding isolates code from other code and reusing methods removes the need for switch statements and other references throughout the code to the system's condition or processing state. This limits the ripple effect of changes and makes it easier to maintain large, complex programs.

The control system of the present invention software contains class libraries, of machining software. These libraries contain machining procedures and functions that can be called with an expected result. These libraries are grouped into object-oriented classes that may be used as is and/or extended. The core libraries contain the most basic characteristics needed for primitive operations.

The software employs a bi-directional messaging interface to facilitate communication between components. Messages are passed between the CNC applications (PPI and Process Class) and Kernel. Communication from the applications to the Kernel differs from communication between the applications in that Kernel communication is more precisely defined for the Kernel. Each component

communicates through messages. These messages may have different requirements. Messages are managed for efficient communication. Unordered, independent messages are executed immediately. Ordered, dependent messages are
5 queued. A queue message is not executed until the previous message is complete, and each component maintains a separate message queue.

A key feature of the CNC control system of the present invention is the ease with which existing systems
10 can be brought onto the new platform. The obvious advantage of this feature is that it preserves features of existing systems while providing a migration path to future technologies. There are two ways a user may take to move existing software to the control system of the
15 present invention: (1) porting 'C' systems for immediate use, or (2) conversion of procedural code to C or C++.

Machine Class

The Machine Class is an object-oriented interface to the Kernel and Process Class. This class contains the
20 machine's device-specific application procedures to hide the complexity of the Kernel and the message interface from the CNC applications. This is accomplished through the interface between the Machine Class and the CNC applications (Process Class/PPI). Applications call
25 standard functions to the Machine Class objects which sends a message to the Kernel. The Machine Class objects handle all communication between the Process Class objects and the Kernel including the creation of the communications port, use of appropriate communication
30 functions, and passing messages back to the CNC applications. The specific Machine Class responsibilities are allocation of resources and connection to the Kernel, message handling between the Kernel and the CNC applications, and device state
35 monitoring and management.

When the system starts up, the Machine Class allocates the resources that the application needs and

creates a port to the Kernel from each CNC application. After the port is created, the Machine Class logs in to the port creating a two-way connection between the Kernel and each running application. This allows messages to be sent back and forth from the applications to the Kernel. Multiple copies of the Machine Class may be used in the system. In fact, it is customary to attach a copy of the Machine Class to each CNC application being used.

Kernel

The Kernel Class is the mechanism through which CNC applications control machinery. The Kernel provides mechanisms for controlling discrete I/O and coordinating motion axes. This general controller can be used in a variety of machining applications. The Kernel contains two components: Logic Controller and Motion Controller. The Motion Controller performs multi-axis coordination. In its basic form, it controls five coordinated axes plus one spindle and two auxiliary axes. In addition it supports several types of interpolation algorithms including linear, circular, elliptical, helical, and polynomial. Applications communicate with the Motion Controller through a message interface. The Logic Controller (LC) engine executes ladder logic/GRAFCET programs to control the machine at the lowest level. There are two programs the LC engine executes: the user program and the system program. The LC also has tools to change, debug, and monitor the operation of the ladder logic.

Operating System

The real-time, UNIX, execution environment provides all of the standard advantages of a real-time environment with its diagnostics and response capabilities. In addition, X Window is a standard, graphical, user interface. X Window permits a variety of input devices (e.g., mice, keyboards, graphic displays) to be simultaneously shared by several programs. This flexibility allows developers to leverage their areas of

expertise without being concerned about the basic system graphics. This window-display interface also allows the user to run one machine and display its output on another, an definite advantage for a CNC application. Motif
5 manages the windows created by X Window. This manager allows the user to control the size, location of windows on the screen, and identification of the active window. This software also provides a library of X Window items to use in system development. TCP/IP is a network protocol
10 that runs on Ethernet. It allows X Window to perform network transparent activities such as remote procedure calls. Its file sharing capabilities means that programmers do not need to download files.

Platform Services

15 The Platform Services Class provides these functions:
Initialization Sequence - a file listing all applications in the order that they will start during power up;

20 Directory Services - a registry of all active applications

Machine Configuration Library - a shared memory area holding default machine parameters;

25 Exception Reporter - collects, organizes, stores and distributes all errors of interest to the active applications

Applications register with Directory Services and receive addresses of the other applications with which they need to communicate. Applications store the addresses they receive from Directory Services in their
30 own directories. Applications, such as the Kernel, that need machine configuration parameters can retrieve those parameters from the shared memory where the Machine Configuration Library stores the information.

35 Messages between the applications use POSIX message queues. These queues, are created at run time and have unique names. Each application receives messages through one instrument, but as when using telephones, each

application can communicate with many different applications.

The Initialization Sequence is the init script file listing all applications in the order that they will start during power up. It is executed after the operating system boots. The Initialization Sequence's primary responsibilities are to:

Load various CNC system drivers (CANbus, MATRIX4, and the serial port driver)

10 Start Directory Services, the Exception Reporter, the Kernel, and the user display

Create the Machine Configuration Library

Start listed applications

A user may create and change this script. It should begin with the device drivers, Platform Services, and the X Window System. Other applications in the script may be the CNC applications and the motion subsystem and Logic Controller within the Kernel. To create or change the script, the customer may use an editor (Vi) or the interactive setup program. The script can also be created automatically with the software installation program. The following is a representative initialization sequence script.

```
#  
25 # Dynamically installed device drivers
```

```
#  
dynaminst \ /Devices/MATRIX4.insttab  
dynaminst \ /Devices/CANbus.insttab
```

```
#  
30 # System Services  
#  
/bin/DirectoryServices  
sleep 5  
/bin/ExceptionReporter
```

```
#  
# Kernel  
#  
/bin/Kernel &
```

```
5 #  
# User Applications  
#  
/Apps/bin/Manual &
```

Platform Services Messages

10 Messages have a standard grammar using command verbs with possible qualifiers. There are three types of qualifiers:

Structure - defines a type of variables.

15 Enumeration - a list of integer values allowing association of constant values with qualifier names.

Union - a variable that may hold (at different times) objects of different types and sizes. It is used to manipulate different kinds of data in a single storage area without embedding any machine-dependent information

20 in the program.

Required qualifiers begin with a capital letter, and optional qualifiers use no capitals.

Message Structure

25 Messages used by the Platform Services have this basic structure:

Verb Qualifiers

A verb describes the message request. The verbs used by the Platform Services' components are -

30 Add - establishes a phone book listing for an application

Get - finds the address of an application or the configuration information in shared memory

Update - supplies new information for an application

Ping - checks on the status of an application (active or shutdown)

Request - asks to be informed when a condition has changed

The qualifiers are data structure names followed by the data structure elements. These qualifiers can be composed of other qualifiers (i.e., dynamic data structures). Verbs act on the qualifiers.

Platform Services Schema

The schema defines the data structure qualifiers for all messages and global data used by Platform Services. Platform Services' messages use the following qualifiers:

- String • PhoneListing
- Description • Value
- FieldPtr • FieldCount
- 15 • DataType • ErrorCode

The following qualifier descriptions contain definitions in the form of text and in 'C' code and the definitions of the 'C' code data names.

String

20 String is a structure describing a collection of ASCII characters. The 'C' data structure follows:

```
typedef struct
```

```
{
```

```
    int length;
```

```
25    char characters[ ];
```

```
} String;
```

length = number of characters in the string

characters = an array of letters, numbers, and/or symbols

30 Description

Description is a string explaining a variable concept (e.g., an error condition) in a message. The 'C' data structure follows:

```
typedef String Description;
```

FieldPtr

FieldPtr is an index in to the Machine Configuration database. The 'C' data structure follows:

```
typedef int FieldPtr;
```

5 FieldCount

If the field is an array the FieldCount indicates the number of elements in the array. The 'C' data structure follows:

```
typedef int FieldCount;
```

10 PhoneListing

PhoneListing is a data structure representing the address of an application in a directory listing. The 'C' data structure follows:

```
typedef struct
```

```
15   {  
        string      processName;  
        portName    Name;  
        int         processID;  
    } PhoneListing;
```

20 processName = name identifying the application
 portName = name of the connection port for the
 application identified
 processID = integer code identifying the application

DataType

25 DataType is an enumeration of data representations. The 'C' data structure follows:

```
typedef enum
```

```
    {  
        undefined;  
30      integer;  
        floatingPoint
```

```
} DataType;
Undefined =    data type not specified
Integer = data consisting of whole numbers
FloatingPoint =    floating point data
5 String = data expressed with characters
```

Value

Value is a union representing a variable data type. DataType defines the data's size and type. The 'C' data structure follows:

```
10 typedef union
{
    int integer;
    double floatingPoint;
    String string;
15 } Value
integer = data consisting of whole numbers
floatingPoint =    floating point data
string = data expressed with characters
```

ErrorCode

20 ErrorCode is an enumeration of exceptions. The 'C' data structure follows:

```
typedef enum
{
    NoSeverity;
25    Information;
    Warning;
    Fatal;
} ErrorCode;
NoSeverity = error of uncategorized severity
30 Information = error message providing information only
(no action required)
Warning = error indicating application is having
difficulty completing the task
Fatal = error indicating application is not able to
35 complete current task
```

Directory Services

Directory Services functions as a registrar for the system applications. The responsibilities of Directory Services are to -

- 5 Maintain a list of applications in the system
- Periodically check (ping) applications to see if they are still running
- Provide queue addresses of registered applications
- Applications register in the Directory Services' phone book by listing their unique ASCII names. Then
- 10 before an application can communicate with another application, it requests the POSIX message queue address from Directory Services' phone book. Each application has its own phone book. It lists only the addresses of other
- 15 applications with which it needs to communicate.

Application Shutdown

- Directory Services periodically pings all registered applications to be certain that they are still running. If an application has shut down, Directory Services removes
- 20 the shut-down application from the list of registered applications, destroys its copy of that application's port connection, and informs all remaining, registered applications that the application has shut down. At that point, the applications decide if they need to disconnect
 - 25 from the shut-down application. Applications clean up after disconnecting by removing the reference for the shut-down application from their own directories.

Messages to Directory Services

- Applications send messages to Directory Services to
- 30 register in the phone book and to retrieve phone book entries of other applications. These messages use the standard message structure described previously.

Add

An application may send an Add message to Directory Services to establish a phone book listing for the application. The Add verb uses the PhoneListing qualifier with the required elements Name, PortName and ProcessID. The message structure is -

Add PhoneListing <Name> <PortName> <ProcessID>

Elements

The elements for the Add verb can use a string of ASCII characters.

<Name>	ASCII character string
<PortName>	ASCII character string
<ProcessID>	number representing the process ID

Sample Message:

Add PhoneListing LC LCport1194 151

Expected Responses

When Directory Services adds the new entry to its phone book, an 'Added' response is sent to indicate that the phone listing was successfully updated. A 'NotAdded' response is sent if Directory Services was not able to update its phone listing.

Added PhoneListing <Name> <PortName> <ProcessID>

NotAdded PhoneListing <Name> <PortName> <ProcessID>

Description <errordescription>

Sample Response:

Added PhoneListing LC LCport1194 151

Get

An application may send a Get message to Directory Services to find the address of an application with which it wishes to communicate. The Get verb uses the PhoneListing qualifier. The message structure is -

Get PhoneListing <ProcessName>

Elements

The ProcessName qualifier is a string of ASCII characters.

<ProcessName> ASCII character string

Sample Message:

5 Get PhoneListing LC

Expected Responses

When Directory Services retrieves an entry from its phone book for a requesting application, it sends a 'Got' response to indicate that the phone listing was
 10 successfully retrieved. A 'NotGotten' response is sent if Directory Services was not able to find the phone listing.

Got PhoneListing <Name> <PortName> <ProcessID>

NotGotten PhoneListing <Name>

Sample Response:

15 Got PhoneListing LC LCport1194 46

Messages from Directory Services

Directory Services sends messages to applications under two conditions:

- Checking to see that the application is still active
 20 (Ping)
- Informing applications that another application is no longer active (Update)

These messages use the standard message structure described previously.

25 Ping

The Ping verb uses the ProcessName qualifier. The message structure is -

Ping <ProcessName>

Elements

<ProcessName> ASCII character string

Sample Message:

Ping LC

5 Update

Directory Services sends the application an Update message to inform an application of a change in another application's status. The Update verb uses the PhoneListing qualifier and has this structure -

10 Update PhoneListing <Status> <description> Elements

<Status> enumeration of status conditions

<description> ASCII string of characters describing the status condition

15 Sample Message:

Update LC shutdown

Machine Configuration Library

The Machine Configuration Library provides default parameters for applications in a shared memory area. This service's responsibilities are to -

Load and distribute initialization parameters from the file system

Distribute parameters to applications

Some common parameters may be maximum acceleration, maximum RPM for the spindle, and travel limits and feed forward gains for each axis. Applications access these parameters under three circumstances:

During application start-up for initialization parameters

During run time when operational parameters are needed

When tuning or another operation makes it necessary for an application to refer to its configuration

5 parameters

This parameter library uses a C++ object, System Variables, to read and write data in the globally accessible shared memory area. The library also contains utilities to create, load the configuration, print, list, 10 save, restore, and remove the information in the System Variables memory region.

System Variables Object

The System Variables object supports seven data types:

Bytes

15 Strings

Doubles

Integers

Short Integers

Long Integers

20 This object also includes methods for saving and reading the parameter information to and from disk. The System Variables methods are listed below:

BasePtr - returns the base pointer to the shared memory.

Close - closes a connection to the shared area.

25 Field - calls the SVField object (described in the following section) to find a field specified by the field name.

FieldCount - gets the number of elements for the field and returns the parameter count.

30 FieldSize - gets the size of the field and returns the parameter size.

FieldType - gets the data type and returns 'B' for byte, 'I' for integer, 'D' for double, 'S' for string, 'H' for short integer, or 'L' for long integer.

FileName - returns the configuration file name used to define the shared data area.

Some additional System Variable methods are listed below:

Get - finds configuration information in shared
5 memory.

Update - places new configuration parameters in shared memory for an application.

GetField - traverses the list of fields in the shared area.

10 Name - returns the shared area name specified in the configuration file.

NumberOfFields - returns the number of fields defined for the System Variables.

PostSemaphore - releases the semaphore used to
15 synchronize access to the shared area.

Remove - deletes the shared area completely from the system.

Restore - places a saved binary copy of the configuration parameters into the shared area.

20 Save - makes a binary copy of the configuration parameters and places it on the disk.

Size - returns the total size in bytes of the shared area (not the amount of shared area being used).

WaitSemaphore - gets the semaphore used to synchronize
25 access to the shared area.

The PostSemaphore and WaitSemaphore methods allow a program to access the shared area and send several messages without the overhead of getting and releasing the semaphore for each Get and Update message. This approach
30 saves time.

SVfield Object

The System Variables object uses the System Variables Field (SVfield) object to describe each field. Using this object improves efficiency of the field access function by

providing detailed field information and eliminating the search for individual fields.

This object contains the following methods:

- Name - supplies the name of the field (up to 31 characters including a null terminator).
- Type - supplies the field data type ('B' for byte, 'I' for integer, 'D' for double, 'S' for string, 'H' for short integer, or 'L' for long integer).
- Count - supplies the number of elements that may be stored under the field name. Elements are numbered beginning with zero.
- Size - supplies the size of each field element. In 386/486 systems, integers and doubles are stored in four bytes while strings are variable length.

15 Utilities

There are several utilities available to create and manage the Machine Configuration shared data and the memory area:

- SVcreate - builds a configuration file.
- SVsize - checks the configuration file's size and recommends a minimum size.
- SVprint - displays the field name, data type (B, I, H, L, D, S), the count (number of elements), and the size of each field.
- SVloadConfig - places the default values into the shared memory area.
- SVlistData - creates a file showing all of the data values currently stored in the shared memory area.
- SVsave - makes a copy of the shared memory area under the file name specified in the configuration file.
- SVrestore - dumps the shared area in hex bytes to be used for detailed debugging tasks.

SVremove - deletes the shared area from the system. The configuration file and any binary 'save' files are left intact.

- SVshmdump - displays the shared area in hex bytes. This
5 can be used for low-level debugging.

Messages to Machine Configuration Library

Applications send messages to the Machine Configuration Library.

Get

- 10 An application may send a Get message to the Machine Configuration Library to access information. It uses this format:

Get Qualifier

Get FieldPtr

- 15 This message requests the <fieldPtr> or the Field Description. If the <fieldPtr> is zero, then this message requests the pointer to the description <name>. If the Description is empty, then this message requests the description of the field pointed to by <fieldPtr>. It is
20 an error if the <fieldPtr> is zero and the Description to be empty.

Get FieldPtr <fieldPtr> Description <name>

Elements

The elements for the Get verb are -

- | | | |
|----|------------|---|
| 25 | <fieldPtr> | Pointer to a field in the Configuration Library |
| | <Name> | Name of the Field |

Sample Message:

Get FieldPtr 0 String "MaxTravelX"

Expected Responses

Configuration Library returns the following:

Got FieldPtr <fieldPtr> Description <name>

NotGotten FieldPtr <fieldPtr> Description <name>

5 Description <errorDescription>

Sample Response:

Got FieldPtr 253 String "MaxTravelX"

Get Description

10 This message is used to request information about the Fields in the Machine Configuration Library. The Fields can be described either by using the name or a field pointer.

Get Description <name> Qualifier FieldPtr <fieldPtr>

Get Description <name> Qualifier Description <fieldName>

15 Elements

The elements for the Get verb are -

<name> name of the information requested from a field:

20 Field Count

Field Size

Field Type

Field value

25 Qualifier The Qualifier is a place holder for the results of the Get. It also specifies the data format (int, float, string) of the desired result.

<FieldName> Name of the field

<FieldPtr> Pointer to the field

Sample Message:

30 Get Description "Field Count" int <count> FieldPtr 23

45

Get Description "Field value" FloatingPoint <value>
 Description "MaxTravelX"

Expected Responses

Configuration Library returns the following:

5 Got Description <name> Qualifier FieldPtr <fieldPtr>
 Got Description <name> Qualifier Description <fieldName>

Sample Response:

Get Description "Field Count" int 10 FieldPtr 23

Get Description "Field value" FloatingPoint 23.5

10 Description "MaxTravelX"

Update

Update Description

This message is used to change information about the
 Fields in the Machine Configuration Library. The Fields
 15 can be described either by using the name or a field
 pointer.

Update Description <name> Qualifier FieldPtr <fieldPtr>

Update Description <name> Qualifier Description
 <fieldName>

20 Elements

The elements for the Get verb are -

<name> name of the information requested from
 a field:

Field value

25 Qualifier The Qualifier is new value for the
 field

<FieldName> Name of the field

<FieldPtr> Pointer to the field

Sample Message:

30 Update Description "Field value" int 10 FieldPtr 23

Update Description "Field value" FloatingPoint 23.6

Description "MaxTravelX"

Expected Responses

The Configuration Library returns the following:

Updated Description <name> Qualifier Field

Ptr <fieldPtr>

- 5 Updated Description <name> Qualifier Description
<fieldName>

Sample Responses:

Updated Description "Field value" int 10 FieldPtr 23

Updated Description "Field value" FloatingPoint 23.6

- 10 Description "MaxTravelX"

Exception Reporter

The Exception Reporter receives all unsolicited error messages (e.g., servo faults) sent by the Kernel. The Exception Reporter responsibilities are to -

- 15 • Receive error reports for applications and Kernel
• Distribute error reports to applications

This makes error handling uniform across all applications. It collects and organizes the errors for applications that have registered with the Exception Reporter to receive
20 particular types of messages. In addition, the Exception Reporter keeps a list of all current pending error messages. When an application starts up and checks in, it can receive all messages of interest to it.

- 25 Applications specify the severity and/or category of errors they want to receive. So an application may tell the Exception Reporter to notify it when any I/O errors are generated. Another application may want to be informed only of the fatal errors that shut down the machine.

Error Messages and Severities

- 30 The Exception Reporter filters errors for applications so that the applications only receive the messages they need.

There are two basic types of messages in the Exception Reporter queue:

One-shot messages

Latched messages

- 5 When a one-shot message arrives, the Exception Reporter determines which applications need to receive the message, sends copies of the message to those applications, and then removes the message from its queue. When a latched message arrives, the Exception Reporter determines which
- 10 applications need to receive the message and sends copies of the message to those applications. However, latched messages are not removed from the queue until another message arrives instructing the Reporter to remove the stored message. The latched messages that have not been
- 15 cleared form the group of current pending messages that a newly started application may need to receive.

The messages may have three severities:

Information - describes a condition that may be of general interest to other applications.

- 20 Warning - indicates that operation of the machine has halted though the power is still on. The operator may need to take some action to continue operations.

Fatal - tells the system applications that the servo amp has been shut down and the power has been taken away from

25 the machine control hardware. The operator must take some action to resume operations.

There are also categories of errors that may be of interest to applications:

Motion

- 30 Logic Control

Device Layer

Directory Service

- Of course, the customer may also define additional error categories. Then when a message arrives, the Reporter
- 35 matches its severity and category with the types of messages each application indicated it wanted to receive.

For example, an application may need only the fatal, motion control messages, and another may need all logic control errors.

- 5 After the messages are filtered in this manner, the one-shot messages are broadcast to all interested applications and removed from the queue. All latched messages are broadcast to interested applications and kept in the queue until specifically removed by another message.

Message Formats

- 10 Messages sent to the Exception Reporter either report an error or request error information. There are two verbs used in the Exception Reporter messages: Update and Request.

Update

- 15 To inform an application of an error condition, the Exception Reporter sends the application an Update message. The Update verb uses the Error qualifier and has this structure -

Update Error <ErrorCode> <description>

- 20 Elements

<ErrorCode> enumeration of exceptions
<description> ASCII string of characters describing the error

Sample Messages:

- 25 Update Error Fatal loss of encoder; X axis

Expected Responses

- The Exception Reporter sends the error message to an application. If the error message was successfully sent, it returns an 'Updated' message. If the error message was not sent successfully, it returns a 'NotUpdated' message.
30 The responses use these formats:

Updated Error <ErrorType>

NotUpdated Error <ErrorType> <ErrorValue> Desc
 <errordescription>
 Request

- 5 An application may send a Request message to Exception Reporter to ask that it be informed of specified error conditions.

Request ErrorCode <Code>

Elements

<Code> enumeration of exceptions

- 10 Sample Message:

Request ErrorCode Fatal

Expected Responses

There are two expected response verbs: Requested and NotRequested. Both verbs use the ErrorCode qualifier.

- 15 Requested ErrorCode <Code>

NotRequested ErrorCode <Code>

Operator Class

- Operator Class applications include part programming software. The conversational language used in a fully-
 20 featured package has a question/answer format using multiple choice and fill-in-the-blank questions, as well as clearly worded operator prompts. To further simplify part programming, the system displays graphic illustrations of plan view, side views, and/or an
 25 isometric view with dimensional scaling in the X, Y, and Z axes.

The conversational part programming package features the following:

- Packaged Cycles
- 30 • Part and Toolpath Graphics Verification for Conversational and NC programs
- Programmable Safety Areas
- 'No-Calc' Programming

- Estimated Run Time
- 99 Tool References
- Automatic Speed and Feed Calculation
- Inch/Metric Programming
- 5 • Modal Parameter Blocks
- Automatic Rough/Finish Pass
- Data Block Search

After the operator completes a part program, there are several additional features of the software that can be
10 used to improve efficiency and accuracy:

- Error Checking
- Test Run Function
- Program Review
- Program Text Printout
- 15 • Graphics Printout
- Upload/Download Utility

The automatic calculation feature allows the system to calculate certain unknown dimensions after sufficient information has been entered. This feature computes and
20 displays Cartesian and polar data for a programmed move. For example, if the 'X' and 'Y' end coordinates are entered, the system automatically calculates the XY length and the XY angle parameters. The XY angle is the angle of the line segment (from start point to end point) measured
25 counterclockwise from the 3 o'clock position. If the XY length and the XY angle are entered, the system calculates the 'X' and 'Y' end coordinates.

Cutter Compensation

When beginning the part program, the operator
30 describes all of the tools that will be used. Then the program can automatically allow for the diameter of the tool when determining the toolpath for an inward spiral or when connecting milling segments. With cutter compensation in use, the tool is offset from the print line a distance
35 equal to the radius of the tool. The operator may also

indicate whether to compensate on the right as in conventional milling or the left for climb milling. If the cutter compensation feature is not needed, the operator does not select it as an active option when programming a
5 block.

Packaged Cycles

Packaged cycles are pre-programmed, common machining operations such as drilling, tapping, pecking, and boring and reaming. Since the system contains packaged cycles,
10 the operator can specify a type of operation and define only the necessary variable information. Then the system makes additional calculations to define the operation fully. For example, when the operator is programming a drilling operation with pecking, the operator simply
15 specifies the peck type and depth and the system uses a canned cycle to determine the exact movements of the drill during the pecking process.

RS-274-D Package

A RS-274-D package provides conventional NC (G-code)
20 programming capabilities. This package allows the operator to save and load part programs to and from remote computers running CAD/CAM applications or other peripheral devices (e.g., paper tape readers). Communication between these devices is handled over RS-232-C serial ports.
25 The NC editor in this package has the following features:

- Character insert or overwrite modes
- Optional sequence numbers
- Automatic sequence numbering by a programmable increment
- 30 • Block-to-block cursor moves (forward and backward)
- Character-to-character and word-to-word cursor moves (forward and backward)
- Jump to program beginning or end or scroll up and down on one page
- 35 • Jump to block or sequence number

- Jump to or replace a matching NC word
 - Automatic syntax checking of NC data blocks
 - 10-element tag queue for 'bookmarking' the program
 - Jump to one of the tags
 - 5 • NC block insert and delete
 - Copy, move, or delete a range of NC blocks
 - Interaction with the graphical system for program verification
- NC programs can be loaded into conversational PPIs through
- 10 this interpreter.

PPI Messages

- The Part Program Interpreter messages have the standard grammar using command verbs with possible qualifiers. There are three types of qualifiers:
- 15 Structure - defines a type of variables.
- Enumeration - a list of integer values allowing association of constant values with qualifier names.
- Union - a variable that may hold (at different times) objects of different types and sizes. It is used to
- 20 manipulate different kinds of data in a single storage area without embedding any machine-dependent information in the program.

Required qualifiers begin with a capital letter, and optional qualifiers use no capitals.

25 Message Structure

Any of the Part Program Interpreters used in the system have the same basic message structure:

Verb Qualifiers

- A verb describes the message request. The verbs used by
- 30 the PPI are -
- Interpret - finds information about the axis positions and speed
- Update - supplies new information about the axis position and speed

The qualifiers are data structure names followed by the data structure elements. These qualifiers can be composed of other qualifiers (i.e., dynamic data structures). Verbs act on the qualifiers.

5 PPI Schema

The schema defines the data structure qualifiers for all messages and global data used by any Part Program Interpreter (PPI). The messages use the following qualifiers:

- 10 • String
- Description

The following descriptions of these qualifiers contain definitions of the qualifiers in the form of text and in 'C' code and the definitions of the 'C' code data names.

15 String

String is a structure describing a collection of ASCII characters. The 'C' data structure follows:

```
typedef struct
```

```
{
```

```
20     int  length;
     char characters[ ];
} String;
```

```
length =  number of characters in the string
```

```
characters =  an array of letters, numbers, and/or
```

```
25 symbols
```

Description

Description is a string explaining a variable concept (e.g., an error condition) in a message. The 'C' data structure follows:

```
30 typedef String Description;
Interpreter Messages
```

Any Part Program Interpreter working in the system must use two standard messages: Interpret and Update.

Interpret

The Interpret messages send pieces of an RS-274 program to the Interpreter.

Interpret Description <programBlock>

- 5 The Interpret message directs the PPI to begin execution of the Part Program.

<programBlock> RS-274 program block

Expected Responses

- 10 If the PPI is able to interpret the program block, it responds with an Interpreted message. If the PPI is not able to interpret the message, it responds with a NotInterpreting message. The expected responses for any of the Interpret commands are -

Interpreted <Qualifier>

- 15 NotInterpreting <Qualifier> Description <errordescription>

Update

An RS-274 program is made up of many modals. The initial values of these modals can be set using the Update message.

- 20 Update Description <modalName> Qualifier

<modalName>	Name of the Modal to be modified
Qualifier	contains data type and a value for the modal.

Expected Responses

- 25 The PPI responds with an Updated message to indicate that the modal has been set. If the modal is undefined, an NotUpdating error message is returned.

Updated <Qualifier>

NotUpdating <Qualifier> Description <errordescription>

- 30 Configuration Parameters

The Integration Tools, described later in this chapter, allow integrators to modify interactively the behavior of the controls as they adapt the controls to the

machines. OEMs can modify the parameters for the following:

- Kinematics
 - Servo Tuning
 - 5 • Safety Regions
 - Maximum Feeds and Speeds
 - Lead Screw Mapping
 - Remote Communications
 - Language
- 10 Version control of configuration files permits the integrator to extend previous versions of parameters and record the changes for backtracking purposes.

Machine Class

The Machine Class of the control system of the present invention forms a device-oriented interface between the Kernel and the CNC applications. The Machine Class establishes and monitors the CNC applications' connections to the Kernel and handles messages between the applications and Kernel. Each application includes a copy of the Machine Class to facilitate a common interface to the Kernel. Also, shared data assures that all applications use the same Machine Class state information.

Since the Machine Class uses object-oriented design, it contains objects that define specific devices with all of the possible functions for each device. For example, a spindle object may have the possible functions of run, clamp, and stop. The object's data describes the speed range and current speed of the spindle. A CNC application may not necessarily use all of a Machine Class object's functions, but the functions are available and supported by the Kernel.

A CNC application may also hook into packaged cycles from the Application Tool Kit. These cycles define common machining operations such as drill, bore, and tap and operate at a higher level in the control system than the Machine Class. By using these same Machine Class object methods, a customer may customize and expand the

packaged cycles to meet specialized needs without concern for the details of Machine Class operations.

Multiple copies of the Machine Class may be used in the control system. It is recommended that a copy of the Machine Class be attached to each CNC application being used in order to provide a common interface to the Kernel. In addition, a customer may extend the functionality of the Machine Class being used, as long as copies of the same Machine Class are being used by all applications.

Described herein are two functional Machine Classes according to the present invention: (1) Milling Machine Class; and (2) Sample, generic Machine Class. The sample, generic Machine Class is a simple example designed to assist in gaining an gain understanding of the message interface. The Milling Machine Class is one that may be implemented for a basic milling machine.

Milling Machine Class

The Milling Machine Class allows customers with milling machines to become immediately operational. To use this Machine Class, customers simply link to the Machine Class library with their CNC application and gain access to the following objects:

- Flow Control
- Push-button Console
- Jog Pendant
- Axis
- Axis Group
- Spindle
- Tool Changer
- Coolant
- Lube

All of these objects allow a CNC application to grab ownership of the device, initialize the device, monitor its current state, and release ownership. When an application has grabbed ownership of a device, it then has

the authority to issue action requests to that device using the methods provided. The Milling Machine Class can also be used in combination with the packaged cycles in the Application Tool Kit to customize the operation of a milling machine.

Sample, Generic Machine Class

A sample Machine Class may be used as a pattern to develop new Machine Classes. It contains the minimum object-oriented devices with their methods that are needed to operate a typical machine tool:

- Flow Control - controls the communication from the CNC application to the Kernel's synchronous queue.
- 15 Push-button Console - reserves all necessary buttons and lights on the console for an application.
- 20 Axis - allows an application to control an individual axis or joint.
- Axis Group - user-defined groups of coordinated axis moves (e.g., X, Y, Z, A, and B).
- 25 Spindle - basic functions of a machine tool spindle.
- Tool Changer - basic functions of a tool changer.
- 30

Shared Memory

In an alternate embodiment of the invention, an area of the computer's memory is reserved for the Machine Class information. The shared memory contains ownership and state information for each device. Each copy of the

Machine Class looks at this region to access information about the devices. However, access to this area is controlled so that applications can only view and change device information through the Machine Class.

5 Rules of Ownership

Since multiple applications may attempt to access the same device, the concept of device ownership is central to the operation of the Machine Class. Ownership of a device means that an application has reserved that device though the application may not be using device at the moment.

The application that 'owns' a device has full access to it while other applications have read-only access. Applications are permitted to send messages to devices only if they have ownership of those devices. This minimizes the inter-component logic required for any application often used to determine permission conditions for a command. However, some decision logic is still needed within each application.

Systems with only a single application may be structured to never grab ownership of a device. In this situation, there would be a single owner of all devices.

Communications

Messages to the Machine Class devices can originate from several sources:

- Part Program Interpreter
- User Interface
- Push Buttons on the Console or Jog

Pendant

- Sensor Interface

To simplify system operations and programming, the control system has a specific division of labor between its components. For example, the Machine Class does not worry about the Kernel's responsibilities such as travel limits and servo errors. Conversely, the Kernel

is not concerned about ownership or devices because the Machine Class handles that exclusively.

This system structure also simplifies system communications and complies with the open systems concept.

5 CNC applications may communicate with the Kernel through any or all of the system layers. For specific functions, the customer's software engineer may bypass a layer and connect an application directly to the next layer or another layer down. This, of course, is accomplished
10 through the standard message formats supplied for each control system component.

Communication Connections

An application may communicate to the system components in two ways: (1) Through the system layers; or
15 (2) Directly to the components. When an application uses the Machine Class layer, three advantages result:

1. Automatic message sequencing to the Kernel components (Logic and Motion Controllers)
- 20 2. Ownership handling for multiple processes
3. Simplified communication to devices

The control system permits communication through the Machine Class layer to the Kernel components. To
25 operate efficiently, a CNC application's part program interpreter and its user interface (also called a man-machine interface-MMI) need the operational simplification provided by the packaged cycles from the Application Tool Kit and the features of the Machine Class.

30 However, some programs do not need the features of these middle layers. For example, the diagnostic and tuning programs within a CNC application are not concerned with the system's devices or ownership rules. These specialized programs can communicate efficiently by
35 connecting directly to the Kernel functions. Another program that bypasses the middle layers is the Exception

Reporter. It is not interested in the machine devices or even the Kernel functions and can connect directly to the messaging functions.

- 5 If a customer is using only one CNC application to control the entire system, that application must manage device access between different parts of the program.

Message Schema

The Machine Class messages use the qualifiers, listed in the schema below, to define the messages.

- 10 Qualifiers are data structure names followed by the data structure elements. These qualifiers can be composed of other qualifiers (i.e., dynamic data structures). The message verbs, described in the following section, act on these qualifiers.

15 String

String is a structure describing a collection of ASCII characters. The 'C' data structure follows:

```

20         typedef struct
        {
                int length;
                char characters[ ];
        } String;
        length -      number of characters in the
25 string          characters -  an array of letters, numbers,
                        and/or symbols

```

Data Type

- 30 Data Type is an enumeration of data representations. The 'C' data structure follows:

```

        typedef enum
        {
                Undefined;
                Integer;
35         FloatingPoint;

```

61

```
        String;
    } DataType;
    Undefined -      data type not specified
    Integer -       data consisting of whole numbers
5    FloatingPoint -  double precision floating
    point number
        String -     data expressed with characters
```

Value

Value is a union representing a variable data
10 type. DataType defines the data's size and type.
The 'C' data structure follows:
typedef union
{
 int integer;
15 double floatingPoint;
 String string;
} Value
integer - data consisting of whole numbers
floatingPoint - floating point data
20 string - data expressed with characters

AxisID

AxisID is an enumeration describing an
individual axis. The 'C' data structure follows:
typedef enum
25 {
 Xaxis;
 Yaxis;
 Zaxis;
} AxisID

30 Group

Group is a structure describing a group of axes.
The 'C' data structure follows:
typedef struct
{
35 int id;
 int numberAxes;

62

```

        AxisID axes[];
    } Group
    id -          Axes group id
    numberAxes -  number of axes in group.
5           Range 1 - NumberAxismax
    axes -        array of AxisID's

State
    State is an enumeration of the current
    conditions of a device. The 'C' data structure
10 follows:
        typedef enum
        {
            Uninitialized;
            Calibrated;
15            Stopped;
            at OrientPosition;
        } State
    Uninitialized -    object has not been
    initialized.
20    Calibrated -    object has been calibrated.
    Stopped -        object is not moving
    OrientPosition -  object has arrived at the
    orient position

ParameterInfo
25    ParameterInfo is a structure describing
    information specific to a device. An example of a
    'C' data structure for a tool changer follows:
        typedef struct
        {
30            int toolID;
            int CarouselPosition;
        } ParameterInfo
    toolID - integer representing the tool
    identification number.
35           Range: 1 - NumberToolsmax

VelocityType

```

VelocityType is an enumeration of velocity representations. The 'C' data structure follows:

```
typedef enum
```

```
{
```

```
5         Undefined;
```

```
        XYZ;
```

```
        XYZAB;
```

```
        Spindle;
```

```
    } VelocityType
```

```
10    XYZ -          velocity for 3 axis machine
```

```
    XYZAB -   velocity for 5 axis machine
```

```
    Spindle - velocity of the spindle
```

Velocity

Velocity is a structure describing speed and direction. The 'C' data structure follows:

```
15
```

```
typedef struct
```

```
{
```

```
        VelocityType type;
```

```
        Value data;
```

```
20    } Velocity
```

type - indicates the type of velocity data in the structure

data - velocity data; Units of (m/sec) for linear axis and (radian/sec) for rotary axis.

```
25
```

Override

Override represents a speed multiplier. The 'C' data structure follows:

```
typedef double Override;
```

```
30    Override -      representation of speed  
                    multiplier. Value of one (1)  
                    indicates 100%.
```

Range: 0.1 - 2.0.

Increment

Increment represents a delta position. The 'C' data structure follows:

```
35
```

```
typedef double Increment;
```

Increment - representation of a delta move.
Units for increments are meters.

Offset

Offset is a structure describing Delta position.

5 The 'C' data structure follows:

```
typedef struct
```

```
{
```

```
    int count;
```

```
    double delta[];
```

10 } Offset

count - number of axes deltas described in
structure.

(range 0 -maxAxes)

15 delta - array of axis deltas. Meters are
used for linear axis, and radian
is used for rotary axis.

Feedrate

Feedrate represents coordinated linear speed of
the Cartesian axes. Feedrate uses units of
20 (meters/second). The 'C' data structure follows:

```
typedef double Feedrate;
```

Linear

Linear is a Qualifier used with "Move" verb to
describe a linear move. The 'C' data structure
25 follows:

```
typedef struct
```

```
{
```

```
    Position endPosition;
```

```
    Attributes attributes[];
```

30 } Linear

endPosition - represents the linear position at
the end of the move

35 attributes - attributes describe condition
that affect the move. 'Until
Limit Switch' is an example of an
attribute.

Tool

65

Tool is a Qualifier used to describe a tool.
The 'C' data structure follows:

```
typedef struct
{
5      int toolID;
      } Tool
      toolID - Integer representing the tool
identification number.
```

Range: 1 - NumberTools_{max}

10 Gear

Gear is a Qualifier used to describe gear ratio.
The 'C' data structure follows:

```
typedef struct
{
15      int gearID;
      double gearRatio
      } Gear
      gearID - integer representing the gear
identification number
20      gearRatio - floating point number
representing the gear ratio
```

Machine Class Message Formats

The Machine Class messages begin with verbs to describe the message requests. These verbs reflect the actions of the methods listed for the device objects described in the next section. In the list below, each verb is defined and possible message formats are shown after the definitions. Many Machine Class verbs stand alone to direct the actions of objects. For those verbs,

30 no message formats are not listed.

Grab

Requests ownership of a specific device.

UnGrab

Releases ownership of a specific device.

35 Initialize

Establishes default parameters necessary to operate a device.

UnInitialize

5 Forces a re-initialization of a specific device (must initialize after this verb is used).

Get

Retrieves the current information from a specific device.

10 Get Description <name> Qualifier
Get <ParameterInfo>

Update

Establishes a specific operational parameter for a device.

15 Update Description <name> Qualifier
Update <Override>
Update <Gear>
Update <Feedrate> <value>

Enable

20 Enables special operation of a specific device.

Enable <Power>

Disable

25 Disables special operation of a specific device.

Disable <Power>

Clamp

Engages the clamp on an axis or spindle.

UnClamp

30 Disengages the clamp on an axis or spindle.

Calibrate

Establishes a reference point for a specific device.

Run

35 Begins continuous operation of a specific device.

Cycle

67

Marks the starting position of a sequential operation of a specific device.

Cycle Description <cycleID>

Move

5 Engages coordinated operation of a specific device

Move Linear

Move Velocity

Move <Increment>

10 Dwell

Begins null operation of a specific device for a specified time.

Dwell FloatingPoint <time>

Stop

15 Ceases operation of a specific device in a manner that makes recovery possible.

Cancel

20 Ceases operation of a specific device immediately (recovery will not be possible).

Step

Engages the predefined operation of a specific device in a forward direction.

UnStep

25 Engages the predefined operation of a specific device in a reverse direction.

Machine Class Objects

30 The Machine Class's objects are representations within the system of the devices on a machine and the functions necessary to manage those devices (e.g., flow control, tool changer, axis, and spindle). All Machine Class objects have two parts: data and methods.

35 The object's methods, are instructions, functions, procedures, or actions that describe what the object does in response to an event. A method belongs to an object and indicates how to perform an action or how to

react to an external event. An application may only access an object's data through its methods, if at all. Methods send messages to perform operations. The Machine Class objects with their methods are described in the following sections.

Flow Control Object

In an alternate embodiment of the invention, the control system's Milling Machine Class's Flow Control object controls the communication between a CNC application and the Kernel's synchronous queue. This object allows a CNC application to set up a communications port to the Kernel and monitor the current state of the Kernel for the application. An application must get ownership of the Flow Control object to gain control of the Kernel's synchronous queue. The following methods are included in this object:

	Grab -	requests ownership of the Kernel's synchronous queue.
	UnGrab -	releases ownership of the Kernel's synchronous queue.
20	Initialize -	establishes default parameters necessary to operate the Kernel's synchronous queue.
25	Get <State> -	gets the current active state of the Kernel's synchronous queue.
	Enable <Power> -	enables power for the Kernel's synchronous queue.
	Disable <Power> -	disables power for the Kernel's synchronous queue.
30	Run -	directs the Kernel to process synchronous requests continuously.
	Stop -	directs the Kernel to stop processing requests from the synchronous queue.
35		

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Cancel - directs the Kernel to stop all activity immediately and flush the queue.

5 Step - directs the Kernel to process a single request in the synchronous queue.

Push-button Console Object

The Milling Machine Class's Push-button Console object allows an application to initialize and reserve all
10 necessary buttons and lights on the console. In this way, the operator can press buttons to control power, start a cycle, hold the motion of the machine, and interrupt an operation while an application monitors these actions. When an operator presses a button, a message is sent to
15 the application controlling that button. If the buttons are not enabled by an application, they are ignored by the Logic Controller.

The following methods are included in this object:

20 Initialize - establishes default parameters necessary to operate the push-button console.

Grab - requests ownership of the push-button console.

25 UnGrab - releases ownership of the push-button console.

Get - requests specified information from system components.

Enable - enables remote operation on the push-button console.

30 Disable - disables remote operation of the push-button console.

Update - establishes a specific operational parameter for the push-button console.

35 Jog Pendant Object

The Milling Machine Class's Jog Pendant object allows an application to initialize and reserve all

necessary buttons and lights on the jog pendant. When an operator presses a button, the Kernel can generate a Move message immediately after receiving an Enable message from an application. If the buttons are not enabled by an application, they are ignored by the Kernel.

The following methods are included in this object:

Initialize - establishes default parameters necessary to operate the jog pendant.

Grab - requests ownership of the jog pendant.

UnGrab - releases ownership of the jog pendant.

Get - requests specified information from system components.

Enable - enables remote operation on the jog pendant.

Disable - disables remote operation of the jog pendant.

20 Axis Object

The Milling Machine Class's Axis object allows an application to control an individual axis or joint. The following methods are included in this object:

Initialize - establishes default parameters necessary to operate an axis.

Grab - requests ownership of an axis.

UnGrab - releases ownership of an axis.

Get <State> - gets the current active state of an axis.

Get <ParameterInfo> - returns current parameters.

Clamp - engages the clamp on an axis.

71

UnClamp - releases the clamp on an axis.

Calibrate - establishes a reference point for an axis.

5 Move <Velocity> - moves the axis at a specified velocity.

Move <Increment> - moves the axis a specified distance.

Stop - halts axis motion.

10 Axis Group Object

The Machine Class's Axis Group object describes a user-defined group of axes. The axis group handles multiple axis motion for coordinated moves such as linear and circular and time-coordinated joint moves (point-to-point). The object defines the axes' kinematics, handles ownership, and includes these methods:

Initialize - establishes default parameters necessary to operate the axis group.

20 Grab - requests ownership of the axis group.

UnGrab - releases ownership of the axis group.

25 Get <State> - gets the current active state of the axis group.

Get <ParameterInfo> - returns current parameters.

30 Move <Linear> - engages coordinated operation of the axis group as defined by the point vector, feedrate, attribute, and termination type.

35 Move <Joint> - engages coordinated operation of the axis group using point-to-point time coordination.

Dwell - pauses in motion defined by time in tenths of seconds.

Update <Group> - (axes) identifies which axes belong to this group.

5 Update <Override> - indicates the feedrate override factor.

Update <Feedrate> - (value) indicates the speed applied to a given Axis Group.

10 Update <Offsets> - indicates the offset used for Part Zero and other general offsets.

The Axis Group object has these additional methods:

15 Enable<Power> - enables power to the axis group

Disable <Power> - disables power to the axis group.

Stop - stops the specified axes.

20 Spindle Object

The Spindle object describes all possible functions of a machine tool spindle. This object grabs ownership of the spindle axis and sends messages to the Logic Controller to initialize, enable, and handle the spindle's orientation angle, the maximum RPMs, and all other necessary operations. This Machine Class object contains the following methods:

Initialize - establishes default parameters necessary to operate the spindle.

30 UnInitialize - forces a re-initialization of the spindle.

Grab - requests ownership of the spindle.

35 UnGrab - releases ownership of the spindle.

Get <State> - gets the current active state of the spindle.

```
Get <ParameterInfo> -    gets current
                           information parameters
                           for the spindle.
```

Run - begins continuous operation of the spindle in the specified direction and at the RPM of the move.

Update <Override> - overrides the speed by a specified factor.

```
Update <Gear> -      initiates a remote
                    .   change of the spindle's
                    gear speeds.
```

Clamp - holds the tool in the spindle.

Unclamp - releases a tool from the spindle.

20 The Spindle object has these additional methods:

Enable - enables remote operation of the spindle's manual push-button.

Disable - disables remote operation of the spindle's manual push-button.

25 Stop - stops motion of the spindle.

Tool Changer Object

The highly detailed Tool Changer object describes all possible functions of a tool changer. This object has access to the data indicating the number of tools in the changer, the current tool in the spindle, and the carousel position. The tool changer grabs ownership of the required resources such as the spindle and axes. The tool changer uses the storage slot number rather than the tool number for positioning. The tool number and related data are included in the Tool database. This object contains the following methods:

- Initialize - establishes default parameters necessary to operate the tool changer.
- 5 UnInitialize - forces a re-initialization of the tool changer.
- Grab - requests ownership of the tool changer.
- 10 UnGrab - releases ownership of the tool changer.
- Get <State> - gets the current active state of the tool changer..
- 15 Get <ParameterInfo> - gets current information parameters for the tool changer.
- Update <Tool>- sets the storage slot number for a tool in the spindle.
- Enable - enables remote operation on the tool changer.
- 20 Disable - disables remote operation of the tool changer.
- Calibrate - sets the indexer position.
- 25 This tool changer object also contains these methods:
- Cycle - marks the starting position of a sequential operation of the tool changer.
- Stop - halts tool changer motion.
- 30 Step - moves the tool changer one logical step at a time.

Coolant Object

The Coolant object describes all possible functions of the coolant mechanism. This coolant object contains the following methods:

35

- Grab - requests ownership of the coolant device.

75

- UnGrab - releases ownership of the coolant device.
- Get <State> - gets the current active state of the coolant device.
- 5 Stop - indicates when to stop the coolant.
- Run - begins continuous application of coolant and identify the type of coolant (mist, flood, or both).
- 10 Enable - enables automatic clearance plane detection and automatic shut-off.
- Disable - disables automatic clearance plane detection and automatic shut-off.
- 15

Lube Object

The Lube object describes all possible functions of the lubrication mechanism. This lube object contains the following methods:

20

- Grab - requests ownership of the lubrication device.
- UnGrab - releases ownership of the lubrication device.
- 25 Get <State> - gets the current active state of lubrication device.
- Stop - indicates when to stop the lubrication.
- Run - begins continuous application of lubrication.
- 30

Kernel-Machine Class Communication Example

The following communication example demonstrates data moving through the Machine Class to the Kernel components. In this example, the CNC application is operating a spindle using the following steps:

35

1. Application grabs ownership of the Spindle. It receives an 'OK' or a 'Reserved' response.

2. Application requests SpindleRun.

3. Machine Class sends these requests to the Motion

Controller:

- 5 • Update <Gear> (directs Logic Controller to activate sequence)
- Wait until LCflag (directs MC to wait for the LC flag)
- Move Velocity <rpm> (directs MC to apply voltage to the spindle axis)
- 10 • Update <Flag> SpindleAtSpeed (directs LC to report when up to speed)
- Wait until LCflag (directs MC to wait for LC flag before continuing)

4. The Motion Controller returns 'OK' or 'Conflict' responses.

5. The Motion Controller sends a SpindleGear request to Logic Controller and waits for LCflag.

6. LC executes spindle enable and gear change logic:

- 20 • spindleOrient = Off
- spindleEnable = On
- spindleOn = On
- select gear speed based on RPM
- 25 7. LC sends request to MC to creep spindle axis.
- 8. MC sends 'atCreep' message to LC.
- 9. C selects gear. If an error occurs an error message is sent to the Exception reporter and the Machine Class flushes the queue.
- 30 10. LC sets LCflag to satisfy first MC Wait (indicates that it is OK to start axis).
- 11. MC begins spinning the Spindle axis based on Move parameters. If an error occurs, send an error message to Exception Reporter, and the Machine Class flushes queue.
- 35 12. MC gives SpindleAtSpeed request to LC.

13. LC waits for SpindleAtSpeed input or time-out.
If an error occurs, send error message to
Exception Reporter, and the Machine Class
flushes queue.
- 5 14. LC sets LCflag to satisfy second MC Wait
(indicates sequence is complete).
15. LC sends Completion response to Application (if
requested by Application).
- 10 16. Machine Class sets DalState = SpindleRunning (if
requested by Application).

Customizing a Machine Class

The open systems design of the control system of the present invention permits modification of the Machine Class to handle machines that have not been used by the control manufacturer. This is possible because the devices are independently defined from the relationships between the devices. The Kernel's Logic Controller and the applications handle the actual device interdependencies during operation.

A system user may add features to a device definition and/or modify the characteristics of the device without being forced to change other devices. This allows the customer to develop an implementation of the system customized for a specific machine.

The Machine Class's object-oriented design allows software engineers customizing the Machine Class to quickly create new Machine Class objects by inheriting from existing Machine Class objects and then modifying them. Because of the advanced programming features of C++, a software engineer need not alter the source code of the control system for the objects in order to modify them. The new objects then inherit the common data characteristics from the parent objects. This feature allows software engineers to build on existing design and code by creating more specific objects from the easily reused code in the existing Machine Class objects.

As with data characteristics, methods can also be inherited from the parent object when a new object is created. Of course, the new object may use the method or create a different version of it. Methods send messages to perform operations. This isolates dependency on a particular data structure thus permitting new features to be added without changing the arrangement of the original objects.

Kernel

The Kernel of the control system provides mechanisms for coordinating motion axes with discrete input/output (I/O) control. This general controller can be used in a variety of machining applications. The CNC applications communicate with the Kernel components, the Logic Controller (LC) and the Motion Controller (MC), through the Machine Class.

Since the control system's software uses object-oriented design and programming techniques, the software components are created from data and functions organized into objects. The Logic Controller and Motion Controller components communicate with each other and with the CNC applications through special objects called messages. These messages use a common message structure, and both have a common message interface. Each component has an asynchronous queue and a synchronous queue. These queues function in the same manner in both controllers.

Messages may be synchronous or asynchronous depending on the requirements of the application. The synchronous messages are ordered and, therefore, dependent on the execution of previous messages in the queue. The asynchronous messages are independent of previous messages so that they can be executed immediately.

Kernel Message

The system messages provide two-way communication between the applications and the Kernel.

components. These messages have the following capabilities:

Single commands

Initialization parameters and configuration sent
through the messages

Synchronous messages are queued

Asynchronous messages are executed immediately

There are different categories of messages:

Flow control

Parameters

Diagnostics

Requests

Data

Error

15 Message Structure

The messages of the control system of the present invention have a standard grammar using command verbs with possible qualifiers and variable attributes.

There are three types of qualifiers:

- 20 Structure - defines a type of variables.
- Enumeration - a list of integer values allowing
 association of constant values
 with qualifier names.
- Union - a variable that may hold (at
25 different times) objects of
 different types and sizes. It is
 used to manipulate different
 kinds of data in a single storage
 area without embedding any
30 machine-dependent information in
 the program.

In the list of messages presented below,
required data elements begin with a capital letter, and
optional elements use no capitals. Messages used by the
35 Kernel have this basic structure:

Verb Qualifiers

A verb describes the message request. Qualifiers are data structure names followed by the data structure elements. These qualifiers can be composed of other qualifiers (i.e., dynamic data structures). Verbs
5 act on the qualifiers.

The verbs used by the Kernel components are -

- Run - is used to control the execution of the synchronous buffer (MC and LC).
- 10 StopRun - is used to control the execution of the synchronous buffer (MC and LC).
- Move - directs the Motion Controller to move along a linear path or move at fixed velocity.
- 15 Wait - tells the MC or the LC to not execute any messages after the Wait message until a StopWaiting message is sent.
- 20 StopWait - tells the MC or the LC to begin executing messages again.
- Get - tells the MC or LC to send information to an application.
- 25 Update - tells the MC or LC that an application wants to change the value of a parameter.
- 30 Flush - tells the Motion Controller to delete all of the messages in its synchronous queue.

Kernel Qualifiers

The Kernel's schema describing the message
35 qualifiers is shown on this and following pages. The

qualifiers define the data structures for all messages and global data used by Kernel.

String

String is a structure describing a collection of ASCII characters. The 'C' data structure follows:

```
5      typedef struct
      {
          int length;
          char characters[ ];
10     } String;
      length - is the number of characters in
              the string.
      characters - is an array of letters,
numbers, and/or symbols.
```

15 Name

Name is a structure that identifies the subject of the message with a descriptive term. The 'C' data structure follows:

```
      typedef String Name
```

20 Description

Description is a structure used to define the basic characteristics of the subject of the message. The 'C' data structure follows:

```
      typedef String Description
```

25 Value

Value is a union representing a variable data type. DataType defines the data's size and type. The 'C' data structure follows:

```
      typedef union
30     {
          int integer;
          double floatingPoint;
          String string;
      } Value
35     integer - is the data consisting of whole
numbers.
          floatingPoint - floating point data.
```

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string - is the data expressed with characters.

PositionType

PositionType is an enumeration of Position representations. The 'C' data structure follows:

```

5      typedef enum
      {
          Undefined;
          XYZ;
10         XYZAB;
          ZS;
          Spindle;
      } PositionType
      XYZ -          position for 3 axis machine.
15     XYZAB -      position for 5 axis machine.
      ZS -          position of the Z axis and
      spindle.
      Spindle - position of the spindle.
```

XYZ

20 XYZ is a structure describing a position for the X and Y and Z axes. The 'C' data structure follows:

```

      typedef struct
      {
          double x;
          double y;
25         double z;
      } XYZ;
      x - position for the X axis.
          Range:  $X_{min} - X_{max}$  (units: meters)
          y - position for the Y axis.
30         Range:  $Y_{min} - Y_{max}$  (units: meters)
          z - position for the Z axis.
          Range:  $Z_{min} - Z_{max}$  (units: meters)
```

XYZAB

35 XYZAB is a structure describing a position for the X and Y and Z and A and B axes. Linear position

is expressed in meters. Rotary position is expressed in radians. The 'C' data structure follows:

```

typedef struct
{
5      double x;
      double y;
      double z;
      double a;
      double b;
10     } XYZAB;
x - position for the X axis.
    Range:  $X_{min} - X_{max}$  (units: meters)
y - position for the Y axis.
    Range:  $Y_{min} - Y_{max}$  (units: meters)
15 z - position for the Z axis.
    Range:  $Z_{min} - Z_{max}$  (units: meters)
a - position for the A axis.
    Range:  $A_{min} - A_{max}$  (units: radians)
b - position for the B axis.
20    Range:  $B_{min} - B_{max}$  (units: radians)

```

ZS

ZS is a structure describing a position for the Z axis and the Spindle. Linear position is expressed in meters. Rotary position is expressed in radians.

25 The 'C' data structure follows:

```

typedef struct
{
      double z;
      double spindle;
30     } ZS;
z - position for the Z axis.
    Range:  $Z_{min} - Z_{max}$  (units: meters)
spindle - position for the spindle.

```

(units: radians)

35 Position

Position is a structure describing a position.
The 'C' data structure follows:

84

```
typedef struct
{
    PositionType type;
    Value data;
} Position
5   type - indicates the type of position
data in the structure.
    data - position data; meters are used
for a linear axis and for a
10   rotary axis.
```

Contact

Contact is an enumeration types of physical contact for attributes. For example, a probe attribute is a move until a probe makes contact or break contact. The 'C' data structure follows:

```
15   typedef enum
    {
        Undefined;
        Make;
        Break;
20   } Contact
    Make - contact is made.
    Break - contact is broken.
```

EnableDisable

25 EnableDisable is an enumeration describing if a attribute is enabled For example, the Feed rate override is enabled or disabled. The 'C' data structure follows:

```
30   typedef enum
    {
        Undefined;
        Enable;
        Disable;
    } EnableDisable
35   Enable - turn on attribute.
    Disable - turn off attribute.
```

TerminationType

TerminationType is an enumeration describing the ending condition of a move. The 'C' data structure follows:

```
5         typedef enum
           {
               Undefined;
               PrecisionEndPoint;
               NoDeceleration;
10     } DecelerationType
       PrecisionEndpoint -      end point of line
                               must be reached
                               with in in-
                               position
15                               tolerance.
               NoDeceleration - Move is part of
                               continuous contour.
                               End point is not
                               important.
```

AttributeType

AttributeType is an enumeration of attributes. The 'C' data structure follows:

```
           typedef enum
           {
25         undefined
               Limit Switch
               Probe
               Overrides
               MotionHold
30         Absolute
               Incremental
               Deceleration
               Concurrent;
           } AttributeType
35     LimitSwitch - indicates that the move is
                   terminated on either make or
                   break of limit switch.
```

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- Probe - indicates that the move is terminated on either make or break of probe.
- 5 Override - enables or disables override for move.
- MotionHold - enables or disables override for move.
- Absolute - position is described in absolute coordinates.
- 10 Incremental - position is described in incremental coordinates.
- Deceleration - deceleration attribute.
- Concurrent - this move can be concurrently executed with another move.
- 15

Linear

Linear is a qualifier used with the Move verb to describe a linear move. The 'C' data structure follows:

20 typedef struct
{
 Position position;
 Attributes attributes;
} Position
25 position - indicates the endpoint of the linear move.
data - attribute modifying the motion description.

VelocityType

30 VelocityType is an enumeration of velocity representations. The 'C' data structure follows:

typedef enum
{
 Undefined;
35 XYZ;
 XYZAB;
 Spindle;

```
    } VelocityType
    XYZ -      velocity for 3 axis machine.
    XYZAB -    velocity for 5 axis machine.
    Spindle -  velocity of the spindle.
```

5 Velocity

Velocity is a structure describing a position.
The 'C' data structure follows:

```
    typedef struct
    {
10        VelocityType type;
        Value data;
    } Position
    type -      indicates the type of velocity
                data in the structure.
15    data -      velocity data; Units of (m/sec)
                for linear axis and (radian/sec)
                for rotary axis.
```

VelocityMove

VelocityMove is a qualifier used with the Move
20 verb to describe a constant velocity move. The 'C'
data structure follows:

```
    typedef struct
    {
        Velocity velocity;
25    Attributes attributes;
    } VelocityMove
    velocity -      indicates the rate and the
                    reference frame of the move.
    attributes -    attribute modifying the
30    motion description.
```

RunAttribute

RunAttribute is an enumeration of Run message
attributes. The 'C' data structure follows:

```
    typedef enum
35    {
        Undefined;
        SingleCycle;
```

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```

        Immediate;
        EndOfCycle;
        MotionHold;
    } RunAttribute
5      SingleCycle - requests that the motion
                      control stop after the end
                      of each cycle.
        Immediate - requests that the motion
10       command be executed
                      immediately.
        EndofCycle - marker for separating moves
                      in a cycle.
        MotionHold - indicates a motion hold
condition.
15      ErrorCode
        ErrorCode is an enumeration of types of error
        codes. The 'C' data structure follows:
        typedef enum
20      {
        NoSeverity;
        Information;
        Warning;
        Fatal;
        } ErrorCode
25      NoSeverity - error of uncategorized
                      severity.
        Information - error message providing
                      information only (no action
                      required).
30      Warning - error indicating application
                      is having difficulty
                      completing the task.
        Fatal - error indicating application
                      is not able to complete
                      current task.
35

```


Motion Controller

The Kernel's Motion Controller performs multi-axis interpolation generating target points for the servo hardware. The Motion Controller supports high speed
5 spindles (up to 60,000 RPM), rigid tapping, encoder jog, and touch probing. An exemplary motion controller has these features:

- * Five (5) coordinated axes plus one (1) spindle
- * Programmable interpolation rate - 5 milliseconds
10 to 20 milliseconds
- * Provides status information for -
 - * position (command and actual)
 - * velocity
 - * following error
- 15 * Leadscrew and backlash compensation using linearly interpolated tables
- * Leadscrew compensation corrects for mechanical error up to 200 times per second
- * 5 millisecond block transfer rate resulting in
20 more detailed information being processed faster
- * Non-linear control for circle compensation
- * Acceleration control regulates velocity,
allowing tighter coordination between more than
one axis while minimizing mechanical wear on the
25 machine
- * Coordinated interpolation with the spindle
- * Programmable calibration and referencing
sequence
- * Enhanced Servo Algorithm interfaces with the
30 motion controller board to monitor machine
position 10,000 times per second

Configuration Parameters of the Motion Controller

The Motion Controller configuration parameters define the travel limits, PID gain parameters, kinematics,
35 and additional miscellaneous parameters.

Travel Limits

This parameter establishes the valid travel limits. They can be negative to positive or positive to negative along the X, Y, and Z axes.

5 PID Gain Parameters

The gain parameters are used for closed loop control of each axis (x to b). These parameters are -

- proportional (P)
- 10 integral (I)
- derivative (D)
- integral limit
- velocity feed forward

15 The parameter values are downloaded to the appropriate hardware for controlling the axis. Then, the modified PID algorithm with velocity feedforward residing on the hardware controls each axis.

The Application Tool Kit may be utilized to set and adjust the parameters.

20 Programmable Kinematics

The user may specify the relationships between axes to support a variety of axis configurations. The forward kinematics determine the position and the orientation of the end-effector given the joint angles. The inverse kinematics determine the joint angle given the position and orientation of the end-effector. The possible kinematics parameters are -

$$\begin{aligned}
 \text{X position} &= X_0J_0 + X_1J_1 + X_2J_2 + X_3J_3 + X_4J_4 \\
 \text{Y position} &= Y_0J_0 + Y_1J_1 + Y_2J_2 + Y_3J_3 + Y_4J_4 \\
 \text{Z position} &= Z_0J_0 + Z_1J_1 + Z_2J_2 + Z_3J_3 + Z_4J_4 \\
 \text{A position} &= A_0J_0 + A_1J_1 + A_2J_2 + A_3J_3 + A_4J_4 \\
 \text{B position} &= B_0J_0 + B_1J_1 + B_2J_2 + B_3J_3 + B_4J_4
 \end{aligned}$$

Miscellaneous Motion Control Parameters

Some additional parameters that can be set by the Motion Controller are -

- * DAC (digital analog converter) balance parameter
- * Maximum acceleration
- * Axis sense
- * Axis resolution
- * Maximum rotary RPM
- * Limit switch to marker pulse (index pulse)
- * Lead screw compensation table

Motion Controller Messages

The messages of the control system are objects, such as C++ objects. Each message object is transmitted in binary form to the receiving application's mailbox and then rebuilt into an object. This section describes the Motion Controller message verbs:

- | | |
|------|----------|
| Run | Update |
| Move | StopRun |
| Wait | Flush |
| Get | StopWait |

Modals establish a condition that persists until another modal changes it. The Motion Controller modals are -

- OverrideEnable
- MotionHoldEnable
- IncrementalEnable
- DecelType

These modals can also be used as one-shot modals within messages to temporarily set a modal value during the execution of the message and restore the mode prior to execution. The concurrent modal, used only as a one-shot modal, tells the system that a message is linked to the next message and that both must be executed as one. This could span more than one pair of messages.

Run

The Run messages are used with the StopRun messages to control the execution of the synchronous buffer. The Run message asks the Motion Controller to start executing messages from its queue.

5 Run <Qualifier>

 Run RunAttribute <attribute>

The Run RunAttribute directs the Motion Controller to begin execution of the messages in the synchronous buffer.

10 attribute> none

 SingleCycle The Run SingleCycle directs the Motion Controller to execute messages in the synchronous buffer a block at a time. Block are delimited by SingleCycleHeader messages.

15

Expected Responses

20 If the Motion Controller is able to begin execution of messages from the synchronous buffer, it responds with a Running Message. If the Motion Controller is not able to execute the messages from the synchronous buffer, it responds with a NotRunning message. The expected responses for any of the run commands are - Running <Qualifier>
25 NotRunning <Qualifier> Description
 <errordescription>

StopRun

30 The StopRun message is sent to the Motion Controller to halt the execution of the message in the synchronous buffer. The motion can halt execution of message immediately (with controlled deceleration of motion) or at a block boundary.
35 Block boundaries are delimited by Cycle Headers.

 StopRun RunAttribute <attribute>

This StopRun message asks the Motion Controller to stop execution of the synchronous buffer.

StopRun RunAttribute <attribute>

attribute>immediate deceleration motion at
the maximum
acceleration rate.

SingleCycle - stop execution at the
first block end
(singleCycleHeader)
with out exceeding
maximum acceleration..

Expected Responses

When the Motion Controller receives a StopRun message, it halts execution of the message in its synchronous buffer and responds with a StoppedRunning message (format below).

StoppedRunning <Qualifier>

Move

The Move message in the Motion Controller has two qualifiers: Linear and Velocity. The Move message uses this basic structure:

Move <Qualifier> <attributes>

Move Linear

The Move Linear message directs the Motion Controller to move along a linear path. The path is defined by the position specified in the message from the end point of the previous move. The message structure is -

Move Linear <Position> <attribute>

Elements

<Position> XYZ

XYZAB

ZS

S

<attribute> until switch <break|make>

until probe <break|make>

find index pulse

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5 override <enable|disable>
 motion hold <enable|disable>
 probe <enable|disable>
 <absolute|incremental>
 decel <type>
 concurrent

Sample Messages:

10 break Move Linear XYZ 10 11.1 12.0 untilSwitch
 findIndexPulse Move Linear XYZA 10.5 20.0 100.1
 Expected Responses
 NotMoving <Qualifier> <attributes>
 15 Description <errordescription>
 Moving <Qualifier> <attributes>
 Move VelocityMove
 The VelocityMove message asks the
 Motion Controller to move its axes at a
 specified velocity.
 20 Move VelocityMove <Velocity>
 <attribute>
 Elements
 <Velocity> XYZ
 XYZAB
 25 XYZABS
 S
 <attribute> until switch
 <break|make>
 30 until probe <break|make>
 find index pulse
 override <enable|disable>
 motion hold <enable|disable>
 probe <enable|disable>
 decel <type>
 concurrent
 35 Expected Responses
 Moving VelocityMove <Velocity> <attribute>

NotMoving VelocityMove <Velocity> <attribute>
Description <errordescription>

Wait

5 A Wait message is usually sent to the Motion
Controller's synchronous queue. The message asks the
controller to not execute past this message until a
StopWaiting message is sent.

Wait Message

Wait message <id>

10 Sample Messages:

Wait message 1152

Expected Responses

Waiting message <id>

NotWait message <id> Description

15 <errorDescription>

StopWaiting Message

The StopWaiting message is sent to the Motion
Controller to cancel a Wait message.

StopWaiting message <id>

20 Expected Response

StoppedWaiting message <id>

Update

25 An Update message is sent to the Motion
Controller when an application wishes to change the
value of a parameter.

Update Name <FieldName> DataType <Type> Value

<Data>

<FieldName>	<Type>	Description
Feedrate	floatingpoint	Sets the value of the
		feedrate to be used by
		the following motion
		blocks
Override	floatingpoint	Set the value for the
		feedrate override.
35 OverrideEnable	EnableDisable	Enable or disables the
		effect of the feedrate
		override

	MotionHoldEnable	EnableDisable	Enable or disables the effect of MotionHold
	Probe	EnableDisable	Enable or disables the ProbeInput
5	ZeroPosition	Position	Set the Zero for the coordinate system
	Header	Header	The Update Header message allow the applications sending the messages to the Motion Controller to embed User Header information into the Queue.

10

Expected Responses

15	Updated Name <FieldName> DataType <Type>
	Value <Data>
	NotUpdated Name <FieldName> DataType <Type>
	Value <Data> Description <errorDescription>

Get

20 A Get message is sent to the Motion Controller when an application wishes to access information from the Motion Controller. The message allows the application to find and read motion control parameters and state variable and motion registers. These registers are -

- 25
- Current position
 - Index position
 - Probe position
 - Commanded position
 - 30 Velocity
 - Following Error

Get Name

	Get Name <FieldName> DataType <Type>
	<FieldName> <Type> Description
35	Probe Position Holds the position of the axes at the

			last probe contact.
5	Index Position	Position	Holds the position of the axes at the last index pulse.
10	Current Position	Position	Gets current position of the axis
	Commanded Position	Position	Gets the commanded position of the axis
15	Following Error	Position	Gets the following error for the axis
20	Velocity	Velocity	Gets the velocity of the axis
	<FieldName>	<Type>	Description
	Override	floatingpoint	Gets the value for the feedrate override.
25	OverrideEnable	EnableDisable	Indicates if Override is enabled.
	MotionHoldEnable	EnableDisable	Indicates if MotionHold is enabled.
	Probe	EnableDisable	Indicates if Probe is enabled.
30	Expected Responses		
	Got Name <FieldName> DataType <Type> Value		
	<Data>		
	NotGotten Name <FieldName> DataType <Type>		

Flush

The Flush message is sent to the Motion Controller when a application wants the Motion Controller to delete all of the messages from its synchronous message queue.

5

Flush <ProcessName>

Expected Responses

Flushed

NotFlushed

10 Motion Controller Notes

The following describes some of the control options which may be desired in the Motion Controller according to the present invention.

Calibration Sequence

15

The Motion Controller contains a programmable sequence of primitives which include:

Move until not limit switch (off)

Move until index pulse

Move to index pulse

20

Update position

Update position offset

Probing

The Motion Controller's probing configuration includes:

25

Move to position on probe head

Move until not probe (off)

Logic Controller

The Kernel's Logic Controller (LC) is an engine that executes logic programs by scanning inputs, executing programs, and then writing outputs to operate the machine tool. The LC has these features:

30

Executes ladder logic programs

Executes GRAFCET programs

Supports local or bussed I/O including CANbus

35 and Pamux

Programmable scan rate down to 20 milliseconds and dependent on the size of the program

Programmable off-line or on-line

Program using existing off-the-shelf products

Supports on-line LC monitoring

Supports on-line I/O monitoring

5 On-line debugging

Simulation

Communicates through messages

Supplies a window-based translator to

convert common, logic control file formats

10 into the LC file format

Optional embedded Logic Controller in hardware

with programmable scans down to 1 millisecond

Logic Controller Messages

15 The messages of the logic control are objects,
such as C++ objects. Each message object is transmitted
in binary form to the receiving application's mailbox and
then rebuilt into an object. Three types of message can
be sent to the Logic Controller:

Synchronous queue control (Run, Stop)

20 Send data (Update)

Access data (Get)

When the Logic Controller receives user-defined messages,
it stores them in its data table. Logic must be added to
the ladder program to evaluate and execute the message.

25 An example of a user-defined message appears in the
following table:

Type	Definition	Data
1	Tool changer	1 - automatic, tool number
		2 - retract
		3 - extend
2	Coolant on/off	0 - off, 1 - on
3	Enable servo power	

100

Run

The Run messages are used with the StopRun messages to control the execution of synchronous buffer. The Run message asks the Logic Controller to start executing messages from its queue.

5

Run <Qualifier>

Run RunAttribute <attribute>

10

The Run RunAttribute directs the Logic Controller to begin execution of the messages in the synchronous buffer.

attribute> none

SingleCycle The Run SingleCycle directs the Logic Controller to execute messages in the synchronous buffer a block at a time. Block are delimited by SingleCycleHeader messages.

15

20

Expected Responses

If the Logic Controller is able to begin execution of messages from the synchronous buffer, it responds with a Running Message. If the Logic Controller is not able to execute the messages from the synchronous buffer, it responds with a NotRunning message. The expected responses for any of the Run messages are -

25

Running <Qualifier>

30

NotRunning <Qualifier> Description

<errordescription>

StopRun

The StopRun message is sent to the Logic Controller to halt the execution of the message in the synchronous buffer. The motion can halt execution of

35

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message immediately (with controlled deceleration of motion) or at a block boundary. Block boundaries are delimited by Cycle Headers.

StopRun RunAttribute <attribute>

5 This StopRun message asks the Logic Controller to stop execution of the synchronous buffer. It uses this format -

StopRun RunAttribute <attribute>

10 <attribute> immediate - deceleration motion at the maximum acceleration rate.

SingleCycle - stop execution at the first block end (singleCycleHeader) without exceeding maximum acceleration.

15

Expected Responses

When the Logic Controller receives a StopRun message, it halts execution of the message in its synchronous buffer and responds with a StoppedRunning message.

20

StoppedRunning <Qualifier>

Wait

25 A Wait message is usually sent to the Motion Controller in its synchronous queue. It asks the Motion Controller to not execute past this message until a StopWaiting message is sent.

Wait Message

Wait message <id>

30

Expected Responses

Waiting message <id>

NotWait message <id> Description

<errordescription>

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Sample Messages

Wait message 1152

StopWait Message

The StopWaiting message is sent to the Motion Controller to cancel a Wait message.

StopWaiting message <id>

Expected Responses

StoppedWaiting message <id>

Update

Update messages are sent to the Logic Controller by Application program to provide information to the ladder program. The message may update a flag in the Logic Controller data table, send a generic message, or provide a new ladder program to the Logic Controller.

Update <Qualifier>

Expected Response

The Logic Controller process Update messages at the beginning of its scan. It responds with a Updated message to indicate that the Update message was successfully executed. If the Logic Controller is not able to perform the Update, a NotUpdated Message is returned.

Updated <Qualifier>

NotUpdated <Qualifier> Description

<errorDescription>

Flag Access Logic
Controller data
table by Names

FlagID Access Logic
Controller data
table by flag id

LCMsg Generic Logic

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Controller Message

Program Loads sections of
the Logic control
message

5 Update Flag

The Update Flag message is used to change a value
in the Logic Controller data table. These messages are
interpreted at the beginning of each LC program scan.
The Flag can be referenced through a Name or an ID.

10 Update Flag Name <FlagName> DataType <Type> Value
 <FlagValue>

 Update Flag ID <FlagID> DataType <Type> Value
 <FlagValue>

Update LCmsg

15 The Update LCmsg is used to send a
 generic message to the Logic Controller.
 The actual message is interpreted by the
 ladder program.

 Update LCmsg <msgType> Size <MsgSize>

20 Value <msg>

Update Program

 An application uses the Update Program
 message to down load ladder program messages
 to the Logic Controller. The Program is down
25 loaded by breaking it up into segments and
 sending the segments to the Logic Controller.
 The 'SequenceNumber' is used to make sure the
 program segments are received in order.

 Update Program ProgramID <ProgId>

30 Sequence <SeqNumber> String
 <progSegment>

Get

 An application sends a Get message to the Logic
 Controller when it wishes to access information from
35 the Logic Controller's data table.

Get Flag Name <FlagName> DataType <Type>

Get Flag ID <FlagID> DataType <Type>

Expected Response

5 The Logic Controller responses to the
Get messages at the end of each of the
ladder program scans. The Got message
is used to return the value of the
requested flag. The NotGotten message
indicates the requested flag was not
10 defined.

Got Flag ID <FlagID> DataType <Type> Value
<FlagValue>

NotGotten Flag ID <FlagID> DataType <Type>

Description <errorDescription>

15 Ladder Logic Programming

The ladder logic programming environment gives the
OEM off-line tools and a controller resident monitor to
customize the LC. There are three components of the
ladder logic programming environment:

20 Ladder Logic Programming Tool (off-line)
Ladder Logic Debug Tool (remotely hosted, serially
linked)

Logic Monitoring Tool (controller resident)

25 The programming environment provides version control for
the logic programs and back-up to any point in the
changes. This feature also allows the OEM to branch off
at a selected point and start new development paths for
new machine strategies.

Programming Tool

30 An OEM can create and change ladder logic programs
using familiar notation and concepts provided in the
Ladder Logic Programming Tool. This tool gives the
developer an easy-to-use off-line, graphical method for
creating, editing, running, testing, and downloading logic
35 control programs for the controller. With the tool the
engineer can design control programs from initial concept

to final operation using top-down design procedures. The following are programming tool's features:

Supports programming in ladder logic:

Coils and Contacts

5 Virtual Coils and Contacts

Timers

Counters

Branches

10 Function Blocks for math (add, subtract, multiply, divide, trig.)

Function Blocks for interface to CNC

Output in 'ANSI-C' source code form for cross-compile to target coprocessor board

15 Outputs a symbol table that may be read by other programs - useful for parameterization and creation of shared data tables

Supports programming in sequential function charts (GRAFCET SFCs)

20 Produces hard copies of program and data documentation

Supports programming in timing diagram form

Version control allows the integrator to make incremental changes with an audit trail

Ladder Logic Debugging Tool

25 The on-line debugging tool runs on a Windows workstation with a serial (RS232) link to the controller. This tool provides the following features:

- 30 * Graphic illustration of the contacts and coils in the ladder program as they energize and de-energize
- * Ability to monitor and set values in the data table including counter and timer accumulators
- 35 * Display of the GRAFCET steps and transitions as they activate and deactivate

- * Ability to command the Logic Controller engine to execute one scan at a time

Logic Monitoring Tool

The real-time Logic Monitoring Tool gives the integrator a way to observe the states, inputs, and outputs of the machinery during cycling on the machine tool itself. The software allows the integrator to watch for timing problems in I/O, facilitates debugging of logic sequences, and helps with machine wiring or switch adjustments.

The features of the Logic Monitoring Tool are listed below:

- * Incorporated into the CNC executive software system
- * Accessible through the CNC's platform diagnostic mode
- * Displays states of inputs and outputs in real-time
- * Allows the integrator to force the states of outputs and view the responses of the inputs
- * Reads from an alias file to attach symbolic names to I/O point definitions on the screen

Motion Control Hardware

The present invention System uses the aforementioned MATRIX4 multi-axis servo controller board. The system's approach to motion control maintains digital control throughout the position, velocity, and current loops as part of the CNC. As a result, the system achieves more precise, faster, and more robust closed loop control than other servo controls. Many control functions are isolated in the motion control software on the host computer. This approach give the user more flexibility when responding to changing industry needs. This also facilitates retrofitting a new CNC on existing machines. The MATRIX4 controller board is a fully digital, 4-axis position and

velocity controller. The board provides constant velocity control as well as spindle orient capability. When coupled with the VECTOR4 daughter board, the system permits the CNC to control DC brush, DC brushless, and AC induction motors and permits most parameters to be programmed dynamically. Dynamic programming allows an engineer to update the motion control parameters immediately when there are changes in the environment or operating conditions.

10 Motion Control Configurations

Due to the system's configuration flexibility, OEMs can use machines with multiple motors. This is possible because the CNC hides the motors from the application software by sending CNC messages through the power modules to maneuver the motors. This structure allows easy swapping of motors without drastic changes in the machine design.

For each controller board, an OEM can configure up to four axes with each axis independently supporting a different type of motor. Four boards can be used together to support up to 16 motors. The power modules between the CNC and the motors are inexpensive replacements for the proprietary drives common in many systems today. These modules can be purchased from many different suppliers.

25 Motion Control Software

The motion control software in the CNC translates part programming requests into basic position and velocity instructions. As shown in the illustration on the next page, the motion control software is divided into functional components. The operator uses the Part Program Interpreter (PPI) software to direct the motion of the axes. The PPI software may make use of pre-programmed, packaged cycles to perform common operations such as drill and tap.

The PPI sends requests to Process or Machine Objects. This software loads the requests and manual operations, such as tool change or coolant on/off, into shared memory.

The Interface Driver software has these functions:

- 5 • Extracts and processes requests from shared memory
- Interpolates motion lines
- Performs leadscrew mapping
- Sends position/velocity targets to the MATRIX4 board

10 The Interface Driver can accommodate simultaneous commands from the host to multiple DSPs. The driver software converts requests from the PPI into position and velocity targets that are fed to MATRIX4 through the Motion Interface. The driver also uses a 'C' library and function prototypes to define commands for the MATRIX4 board.

15 The 'C' library in the driver software defines the following:

- Axis designators
- Module designators
- Multiple read parameter types
- 20 • Disable interrupts masks
- Servo modes of operation
- Axes per module
- Maximum number of axes per module
- Output loop gains
- 25 • Control Law indices
- Control PID gain indices
- Error codes
- Maximum and minimum velocities and accelerations
- Block transfer rate codes
- 30 • Function prototypes

The motion control software also includes utilities to program the motor technology for the application. These utilities permit engineers to configure, tune, and

maintain applications as well as document system performance.

The MATRIX4 board accepts the motion commands and closes the servo control loop. Since axes move by having voltages applied to them, the MATRIX4 board converts the position/velocity instructions into voltages (0 to 10 volts) and applies the voltages to the axes being controlled. The MATRIX4 board does not need to understand the machine tool's operation since that function is handled by the software.

Machine Configuration Library

The Machine Configuration Library provides default parameters for applications in a shared memory area. This service's responsibilities are to -

- * Load and distribute initialization parameters from the file system

- * Distribute parameters to applications

In one embodiment, this parameter library uses a C++ object, SystemVariables, to read and write data in the globally accessible shared memory area. The library also contains utilities to create, load the configuration, print, list, save, restore, and remove the information in the SystemVariables memory region.

The information in this section provides the details necessary for an engineer who wants to modify or develop new configuration programs. For more general information about these functions, refer to the 'Platform Services' discuss herein.

Defining the Configuration File

In development work for this platform service, the first step is definition of the configuration file containing the system parameters. An ASCII file may be used to define the shared variable name, its size, and each data field in the shared memory. For example:

```
# This is an example configuration
# GT. 11/19/92
```

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NAME /mnt/mydirectory/sharedfilename

SIZE 4096

SOF

	# NAME	TYPE	COUNT	SIZE
5	kTermsX	INTEGER	4	
	kTermsY	INTEGER	4	
	kTermsZ	INTEGER	4	
	kTermsS	INTEGER	4	
	iTermsX	INTEGER	4	
10	iTermsY	INTEGER	4	
	iTermsZ	INTEGER	4	
	iTermsS	INTEGER	4	
	vTermsX	INTEGER	4	
	vTermsY	INTEGER	4	
15	vTermsZ	INTEGER	4	
	vTermsS	INTEGER	4	
	i_limit	DOUBLE	4	
	max_accel	DOUBLE	4	
	pwm_freq	INTEGER	4	
20	lines	INTEGER	4	
	poles	INTEGER	4	
	hall	INTEGER	4	
	deadband	INTEGER	4	
	loopType	INTEGER	4	
25	motorParam	INTEGER	4	
	field	INTEGER	4	
	motor	INTEGER	4	
	Travellimits	DOUBLE	3	
	Units	STRING	1	7

30 The first two lines for the SystemVariables configuration file are comments beginning with the '#' sign. All keywords must be in capital letters in the file. The second line uses the NAME keyword to specify the name of the SystemVariables file. An absolute path name should be used. The third line specifies the size of the data area

35 using the SIZE keyword. The size should be specified in 4K increments, even if the data space used is less than

that. The SOF (start of fields) keyword must precede the defined fields.

The six supported field types are byte, string, double, integer, short integer, and long integer. The first column identifies the name of the field. Field names are limited to 30 characters plus a null terminator making it a total of 31 characters. The second column defines the field type, string, double and integer. There is no limit to the length of a string. The third column defines the number of elements to be stored for that field name. The example shows the field 'kTermsX' to contain 4 integers, 'TravelLimits' 3 doubles and 'Units' 1 string containing 7 characters (including any null terminator).

At this time, the SIZE field is used only for the string data type. It indicates the length of the string (including null terminator).

Utilities

After creating a configuration file, the engineer needs to set up the memory area and load the configuration parameters. The library contains utilities to create the shared memory area, load the configuration, print, list, save, restore, and remove the information in the SystemVariables memory region. These utilities are -

- SVsize
- SVcreate
- SVprint
- SVloadConfig
- SVlistData
- SVsave
- SVrestore
- SVremove
- SVshmdump

These utilities are described in the order they are most commonly used beginning with the SVsize utility.

35 SVsize

The first utility an engineer may need, SVsize, establishes the size of the shared memory. In the

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example below the 4096 SIZE value provides enough space for the defined shared data area. The Total Bytes Used parameter indicates the total amount of space required for the shared data definition that the engineer specified. This figure must be increased up to the next 4K value and used as the SIZE parameter in the configuration file.

Sizing

```

10  [/mnt/mydirectory/sharedfilename]
    Size Indicated [4096]
    Header          [12]
    Table           [1100]
    Data            [431]
    Total Bytes Used [1543]
15  Available Bytes [2553]
    Size Completed.

```

SVcreate

After defining the shared data area, the engineer may create the shared data area using the SVcreate utility. Below is an example using this utility program.

```

20  Building..[/mnt/mydirectory/sharedfilename]
    Size.....[4096]
    Shmid.....[/mnt/mydirectory/sharedfilename]
25  created.
    kTermsX
    kTermsY
    kTermsZ
    kTermsS
30  iTermsX
    iTermsY
    iTermsZ
    iTermsS
    vTermsX
35  vTermsY
    vTermsZ
    vTermsS

```


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```

i_limit
max_accel
pwm_freq
lines
5    poles
    hall
    deadband
    loopType
    motorParam
10   field
    motor
    TravellLimits
    Units
    Bytes Used.....[1543]
15   Available Bytes.[2553]
    Build Completed.

```

SVprint

Once the shared data area has been created, the engineer may display the data description using the SVprint utility. The SVprint utility displays the field name, data type (B, I, D, S, H, L) the count (number of elements) and the size of each String field. Below is an example showing integer (I), double (D) and string (S) data types. This utility also shows the size of each string field.

```

NAME.....[/mnt/mydirectory/sharedfilename]
SIZE.....[4096]
Name      Type Count      Size
-----
30   TravellLimits    D      3
    Units             S      1      7
    deadband          I      4
    field             I      4
    hall              I      4
35   iTermsS           I      4
    iTermsX            I      4
    iTermsY            I      4

```

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	iTermsZ	I	4
	i_limit	D	4
	kTermsS	I	4
	kTermsX	I	4
5	kTermsY	I	4
	kTermsZ	I	4
	lines	I	4
	loopTyp	I	4
	max_accel	D	4
10	motor	I	4
	motorParam	I	4
	poles	I	4
	pwm_freq	I	4
	vTermsS	I	4
15	vTermsX	I	4
	vTermsY	I	4
	vTermsZ	I	4

SVloadConfig

Next the engineer may load default values into the shared memory using the SVloadConfig utility. This utility uses an ASCII file describing the values assigned to each field. The format of the file follows:

These are the default values used for SharedVariable example programs.

	#	FieldName	Index	Value
		kTermsX	0	7000
		kTermsX	1	30000
		kTermsX	2	12000
30		kTermsX	3	19400
		#		
		kTermsY	0	0
		kTermsY	1	20000
		kTermsY	2	5000
35		kTermsY	3	7000
		#		
		kTermsZ	0	2000

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	kTermsZ	1	18000
	kTermsZ	2	3000
	kTermsZ	3	5350
	#		
5	kTermsS	0	7000
	kTermsS	1	30000
	kTermsS	2	12000
	kTermsS	3	19400
	#		
10	iTermsX	0	0
	iTermsX	1	15000
	iTermsX	2	4000
	iTermsX	3	0
	#		
15	iTermsY	0	0
	iTermsY	1	28000
	iTermsY	2	15000
	iTermsY	3	0
	#		
20	Units	0	Metric

In the SVloadConfig utility, lines beginning with a # sign are interpreted as a comment. The first column specifies the field name while the second column is the index. The fields or indexes do not have to be defined in any specific order. The third column is the value. If a field cannot be found or a value is invalid, an error message is printed.

SVlistData

The engineer may list all the data values that are currently stored in the shared area using the SVlistData utility. This utility outputs a file that can be read using the SVloadConfig utility. The value for each field by index is printed.

SVsave

After modifying the data stored in the shared area, an engineer may want to save the information to

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disk. This can be done using the SVsave utility.
Below is an example using this utility.

```
NAME.....[/mnt/mydirectory/sharedfilename]
SIZE.....[4096]
```

5 Save Completed

The save utility saves the shared area under the filename specified in the configuration file with a .sav extension.

SVrestore

10 To restore a previously saved file, use the SVrestore utility. Below is an example using this utility:

```
NAME.....[/mnt/mydirectory/sharedfilename]
SIZE.....[4096]
```

15 Restore Completed

SVshmdump

20 There is another utility, SVshmdump, that may be of interest for debugging the shared area at a very low level. This program dumps the shared area in hex bytes and is useful when the engineer wants to inspect the shared area.

Shared Memory Organization

25 The SystemVariables area can be described as a contiguous area of shared memory. This memory is divided into three sections:

- Shared Memory Storage Header
- Table of Contents
- Data Storage

The header is divided into three fields:

30 Number of fields defined in the shared area
(first 4 bytes)

Offset into the shared area (used when allocating space for new fields)

35 An integer storing the semaphore handle (used to synchronize access to the data area only)

The header structure is as follows:

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```
typedef header {  
    int      number_of_fields;  
    long     offset_into_datastorage;  
    int      semaphore;  
5    } header ;
```

The second four bytes of the header contain a long integer (also four bytes) of the offset into the shared area. This value is used when allocating space for new fields in the shared area. In this scheme the table of contents (the field descriptions) grow downward while the data storage area grows upward. Finally, the header information contains an integer storing the semaphore handle used to synchronize access to the data area only. This means the semaphore is not used when getting information about the fields, but only for reading and writing into the data area.

Note: The byte sizes described in this document for integer and double reflect those of a 386 and 486 architecture.

The second section of the shared area is the table of contents. This area contains a series of field descriptions each can be described using this data structure:

```
#define FIELD_NAME_LENGTH 31  
typedef struct field_description  
{  
30     char fieldname [FIELD_NAME_LENGTH];  
     char type;  
     unsigned int  count;  
     unsigned int  size;  
     unsigned int  offset;  
35 } field_description;
```

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The first 31 bytes of each field description contains the field name. This is the same name that is used in the configuration file. At this time an upward limit of 31 characters (including Null terminator) is allowed. The next byte in the description indicates the field data type. The six field data types are represented by these letters:

5
10
B - byte
I - integer
D - double
S - string
H - short integer
L - long integer

15 The next four bytes describe an integer representing the number of elements to be stored under this name. This can be considered an index into an array beginning with the index zero for the first element. An integer representing the size of each element is stored after the count. Doubles use eight bytes and integers four, with user defined the string sizes. The final four
20 bytes of the field description contains the offset from the beginning of the shared area into the data storage area where the stored values are kept for the field.

Writing a Program

25 An engineer wishing to write a program to access the shared memory area may want to examine the following example. This program simply creates a SystemVariables object, passing the configuration filename to the object. Calls are made to the SystemVariables object for getting
30 the size, mapping the fields to field objects, getting and updating data, and other necessary actions.

```
#include <stream.h>
#include "SystemVariables.hpp"
main (int argc, char *argv[])
35 {
```

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```
int      error;
double   doubleValue;

if (argc < 2)
{
5      cout << form("Usage: %s configuration-
      filename\n", argv[0]);exit (-1);
}
/* Instantiate a SystemVariables object,
specifying the configuration file name to be used
10 */
SystemVariables systemVariables(argv[1], error);
/* Check the error code returned from the
constructor call */
if (error)
15 {
    perror ("SystemVariables Constructor");
    exit (-1);
}
/* The Size method call is one of many calls
20 that will return information about the shared area
*/
if (systemVariables.Size() == 0)
{
    perror ("Invalid size");
25    exit (-1);
}

/*
Here is a simple call to get the value stored in
the 0th index of the field called "max_accel".
30 */
error = systemVariables.Get("max_accel" ,
doubleValue, 0);
cout << form ("max_accel value
[%f]\n",doubleValue);
```

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```

/*
    Finally, close the connection to the shared
data area.

```

```

*/
5      if ((error = systemVariables.Close()))
    {
        perror ("Cannot close shared area!");
    }
}

```

10 Below is the make file used to compile and link this program:

```

CFLAGS=-X -I/usr/local/include
OBJ=./
EXE=./
15 LIB=/usr/local/lib/
OFILES= $(OBJ)example.o
$(EXE)example: $(OFILES)
               g++ -X $(OBJ)example.o $(LIB)libSV.a-o
$(EXE)example

```

```

20 $(OBJ)example.o : example.cc
               g++ -c $(CFLAGS) example.cc -o

```

\$(OBJ)example.o
The SystemVariables methods are described in the following section.

25 SystemVariables Methods

The Machine Configuration Library uses an object, such as a C++ object, SystemVariables, to read and write data in the globally accessible shared memory area. The SystemVariables methods are defined below and the possible return values are listed for each method.

30

BasePtr

This class method returns the base pointer to the shared area. The function prototype for this method is

-

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```
char *BasePtr ( )
```

```
Return Values:
```

```
A non Null pointer on success.
```

Close

5 This class method closes a connection to the shared area. The function prototype for this method is

-

```
int Close ( )
```

```
Return Values:
```

10 0 - Success

 -1 - Error. Check 'Errno' for a description of the error.

An error may occur during an unmap call of the shared area or a close call to the shared area file. Errno is set when these errors occur.

15

Description

This class method returns a character string describing the field. The string contains the field name, type, count and size (in case of string types).

20 The calling program must perform a delete on the returned description. The application may use the Field or GetField method calls to obtain the Field parameter used in this call. The function prototype for this method is -

25 int Description (svField &field, char *description)

```
See Also: GetField, Field
```

Field

30 This method finds the Field for the field specified by fieldName. The function prototype for this method is -

```
int Field (char *fieldName, svField &field)
```

```
Return Values:
```

35 0 - Success

 -2 - Cannot find field.

 -3 - Shared Area Not Initialized.

```
See Also: Get, Update.
```

FieldCount

This method gets the number of elements for the field specified by fieldName. The count is returned in the parameter count. The function prototype for this method is -

5 int FieldCount (char *fieldName, int &count)

Return Values:

- 0 - Success
- 2 - Cannot find field.
- 10 -3 - Shared Area Not Initialized.

FieldSize

This method gets the size of the field specified by fieldName. The size is returned in the parameter size. The function prototype for this method is -

15 int FieldSize (char *fieldName, int &size)

Return Values:

- 0 - Success
- 2 - Cannot find field.
- 20 -3 - Shared Area Not Initialized.

20 FieldType

This method gets the data type for the field specified by fieldName. The type returned in the parameter type is I for integer, D for double, S for string, B for byte, H for short integer, and L for long integer. The function prototype for this method is -

25 int FieldType (char *fieldName, char type)

Return Values:

- 0 - Success
- 2 - Cannot find field.
- 30 -3 - Shared Area Not Initialized.

FileName

This class method returns the configuration filename used to define the shared data area. The function prototype for this method is -

35 char *FileName()

Get

This method retrieves the value stored for a given field by name.

```
int Get (char *fieldName, int    &data, int index)
int Get (char *fieldName, char   *data, int index)
5  int Get (char *fieldName, double &data, int index)
```

The index parameter is optional. If it is not used, the 0th index is searched. Care must be taken when getting string values.

The engineer must make sure the character pointer that is passed into this method has allocated enough space to store the character string. A good way to do this is to use the FieldSize method to get the size of the character string. Then allocate the space before calling this method.

Return Values:

```
0    - Success,
-1   - Invalid field type.
-2   - Field not found.
20  -3   - Shared Area Not Initialized.
    -4   - Invalid Index.
```

The Get method also retrieves the value stored for a given field as specified by the sfField reference.

```
int Get (sfField &field, int    &data, int index)
25  int Get (sfField &field, char   *data, int index)
    int Get (sfField &field, double &data, int index)
```

The Field pointer is found using the Field or GetField methods. The engineer must make sure the character pointer that is passed into this method has allocated enough space to store the character string. A good way to do this is to use the FieldSize method to get the size of the character string. Then allocate the space before calling this method.

Return Values:

```
0    - Success,
```

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- 1 - Invalid field type.
- 3 - Shared Area Not Initialized.
- 4 - Invalid Index

See Also: Field, GetField,

5 FieldSize.

GetField

This method call is used to traverse the list of fields in the shared area. By using a zero in the parameter data you will begin at the top of the list. After each call the data parameter will be incremented. The list can be traversed by calling this method successively until a return value of -1 is return. The function prototype for this method is -

```
int GetField (svField &field, int &data)
```

15

Return Values:

- 0 - Success
- 1 - End of list.
- 3 - Shared Area Not Initialized.

See Also: Get, Update.

20

Name

This class method returns the shared area name specified in the configuration file. The function prototype for this method is-

```
char *Name ( )
```

25

NumberOfFields

This class method returns the number of fields defined for the SystemVariables. The function prototype for this method is-

```
int NumberOfFields( )
```

30

Remove

This class method will remove the shared area completely. After this call no other applications will be able to access the shared area. The function prototype for this method is-

35

```
int Remove ( )
```

Return Values:

- 0 - Success

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- 1 - Error occurred during an unmap call or close call to the shared area file. Check errno for a description of the error.
- 3 - Shared Area Not Initialized.
- 4 - Cannot unlink the shared area file.
- 5 - Cannot unlink the shared area

semaphore.

Save

10 This class method will save a copy of the shared area to disk. The file name will use the shared memory name with a suffix of save. The function prototype for this method is-

int Save ()

15 Return Values:

- 0 - Success
- 1 - Cannot open the save file.
- 3 - Shared Area Not Initialized.

20 Refer to the description of the 'Restore' method for more information.

Restore

This method will restore a saved copy of the shared area. When using the Save and Restore methods a filename with the .sav extension is used. The function
25 prototype for this method is-

int Restore()

Return Values:

- 0 - Success
- 1 - Cannot open the restore file.
- 30 -3 - Shared Area Not Initialized.

The Save and Restore methods use the shared area name with a .sav extension appended to it as a filename for saving and restoring a shared area. The file
35 is saved in a binary format and can only be read using the Restore call. Use the SVlistData utility program to create an

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ASCII readable file of the current field values.

Size

5 This class method returns the total size in bytes of the shared area (not the amount of shared area being used). The function prototype for this method is-

```
int Size( )
```

Update

10 The Update method replaces the value stored for a given field with the value given in data.

```
int Update (char *fieldName, int data, int index)
```

```
int Update (char *fieldName, char *data, int index)
```

```
int Update (char *fieldName, double data, int index)
```

15 the index parameter is optional. If it is not specified the 0th index is used. When updating a string field type the field size will limit the number of characters stored. For example, if you have a character string of thirty characters and you update a field that can only hold twenty, only the first

20 twenty characters will be stored.

Return Values:

- 0 - Success,
- 1 - Invalid field type.
- 25 -2 - Field not found.
- 3 - Shared Area Not Initialized.
- 4 - Invalid Index

The Update method also replaces the value stored for a given field as specified by the sfField reference.

30 int Update (sfField &field, int data, int index)

```
int Update (sfField &field, char *data, int index)
```

```
int Update (sfField &field, double data, int index)
```

The Field pointer can be found using the Field or GetField methods.

35 Return Values:

- 0 - Success,
- 1 - Invalid field type.

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- 3 - Shared Area Not Initialized.
- 4 - Invalid Index

See Also: Get, Field. GetField.

Semaphore

- 5 This method returns the semaphore handle used to synchronize access to the shared area. The function prototype for this method is-

int Semaphore ()

PostSemaphore

- 10 This method call will release the semaphore used to synchronize access to the shared area. You must use the WaitSemaphore method call to get the semaphore before calling this method. The function prototype for this method is -

- 15 void PostSemaphore ()

WaitSemaphore

- This method call will get the semaphore used to synchronize access to the shared area. The call will pend until it can get the semaphore. The function prototype for this method is -

void WaitSemaphore ()

- The WaitSemaphore and PostSemaphore calls are used to allow a program to get access to the shared area and make several calls without the overhead of getting and releasing the semaphore with each get/update call.

- 25 This call should be used in conjunction with the PostSemaphore method call. In some cases an application may want to update or get data for a group of fields without having to get the semaphore for each call.

- 30 In this case the application would make a call to WaitSemaphore, then update/get data for all the fields followed by a PostSemaphore call. Care must be taken when performing this call so as not to hold up other processes for too long a period. This method will save 35 microseconds from each get/update call.

SVfield Methods

The SystemVariables class uses an SVfield class to describe each field within the SystemVariables. To get a reference to individual fields, use the GetField or Field method calls in the SystemVariables class. By getting an SVfield reference, the engineer greatly improves the efficiency of accessing fields in the SystemVariables because this eliminates the search for the individual field. In addition, this provides information about individual fields by making calls to the SVfield class methods. This section describes the SVfield class method calls.

Name

This class method returns the name of the Field. Field names are currently limited to 31 characters including the Null terminator. The function prototype for this method is-

```
char *Name ( )
```

Type

This class method returns the field data type. The return value may be I (integer), D (double), S (string), B (byte), H (short integer), or L (long integer). The function prototype for this method is-

```
char Type ( )
```

Count

This class method returns the number of elements that may be stored under this field name. Elements are numbered beginning with 0. For example, an integer field with a count of five may be accessed using an index from 0 to 4. The function prototype for this method is-

```
int Count ( )
```

Size

This class method returns the size of each field element. Under the Lynx OS (for 386/486 systems) integers and doubles are stored in four bytes, strings are stored by any size. For example, a string field

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with a count of seven and a size of ten means there are seven character strings of length ten (including the Null terminator). The function prototype for this method is-

```
5      int  Size ( )
```

Exception Reporter

The error codes used to filter error messages are available in the file 'ErrorCodes.hpp.' This file may be modified and expanded to meet the customer's needs.

```
10      #ifndef _ERRORCODESHPP
      #define _ERRORCODESHPP
      #
      # FileName:  ErrorCodes.hpp
      #
15      # $Header$
      # $Log$
      #

      static char *ERRORCODESHPPRC string = "$Header$";

      typedef enum ExceptionSeverityValues
20      {
          NO_SEVERITY      = 0x0000,
          INFORMATION      = 0x0001,
          WARNING          = 0x0002,
          FATAL            = 0x0004,
25      All_SEVERITIES = 0x0007,
      } ExceptionSeverityValues;

      typedef enum ExceptionCategoryValues
      {
          NO_CATEGORY      = 0x0000,
30      MOTION              = 0x0001,
          LOGIC_CONTROL    = 0x0002,
          DEVICE_LAYER     = 0x0004,
          DIRECTORY_SERVICE = 0x0008,
```

```

                                130
                                RESERVED_10    = 0x0010,
                                RESERVED_20    = 0x0020,
                                RESERVED_40    = 0x0040,
                                RESERVED_80    = 0x0080,
5                                USER_DEFINED_01    = 0x0100,
                                USER_DEFINED_02    = 0x0200,
                                USER_DEFINED_04    = 0x0400,
                                USER_DEFINED_08    = 0x0800,
                                USER_DEFINED_10    = 0x1000,
10                               USER_DEFINED_20    = 0x2000,
                                USER_DEFINED_40    = 0x4000,
                                USER_DEFINED_80    = 0x8000,
                                ALL_CATEGORIES = 0xFFFF,
                                }ExceptionCategoryValues;

15                               typedef enum ErrorCodes
                                {
                                    EX_NO_ERROR,

                                    EX_NOT_FOUND,
                                    EX_REPLACE_ME_001,
20                               EX_REPLACE_ME_002,
                                    EX_REPLACE_ME_003,
                                    EX_REPLACE_ME_004,
                                }

```

Machine Class

25 Creating a New Machine Class

Creating a completely new Machine Class is a more complex process than simply modifying an existing Machine Class. A customer may create a new Machine Class for one of the following reasons:

- 30 * Existing Machine Classes do not contain the objects needed to operate the customer's extremely specialized machine
- * The customer wants to replace the messaging interface.

* The customer has a specialized Kernel and needs to develop a Machine Class to communicate with it. As with all development efforts there are two main stages: preparation and development.

5 Preparation

To prepare for development of a completely new Machine Class, the customer should analyze the target machine tool to identify all of its devices.

The customer must also identify the system tools to assist in this effort. Some of these tools are -

- OS utilities
- ANSI C compiler
- C++ programming features (compiler, inheritance of object characteristics, and isolation of changes)
- UNIX-based development tools

The customer needs to become familiar with two important control system components:

- * Well-documented Kernel interface including message parameters and Logic Controller flags (in this manual)
- * Full source code for the sample, generic Machine Class

An understanding of these two components simplifies the development effort by helping the customer to connect the new Machine Class to existing Kernel functions.

Development Steps

The steps a developer should follow when creating a new Machine Class are as follows:

1. After a thorough analysis of the target machine, name all of the devices needed to operate the machine. These become the new Machine Class objects.
 2. Identify all of the methods used by each device.
- It is often helpful to use the same verbs as those

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used by existing Machine Class objects. In that way, the developer can connect and use the existing messages.

- 5 3. Match the available Kernel functions to the new Machine Class objects. Create new messages where needed.

10 Those of skill in the art will appreciate that many variations to the invention as described herein may be made without departing from the spirit and scope of the invention, and such variations are within scope of the below claims.

CLAIMS

1. A machine tool control system for a machine tool of the type comprising a controllable, movable tool for shaping a workpiece, means for receiving control
5 instructions describing shaping functions to be performed on the workpiece, a processing unit and memory means, said control system comprising means for receiving and storing in memory means workpiece shaping instructions; means for transmitting command signals to a movable tool to thereby
10 cause the tool to move; characterized by an object oriented software program comprising a plurality of transmitting objects, a plurality of receiving objects, a plurality of messages wherein the plurality of messages are transmitted to the plurality of receiving objects by
15 the transmitting objects, and a motion controller software module for receiving messages from at least one of the plurality objects, the received messages including commands indicating desired movements of a movable tool, the motion controller software module further comprising
20 means for sending command signals to the transmitting means to thereby cause the movable tool to move.

2. The machine tool of Claim 1 characterized in that at least one of said objects comprises a model of a shaping process to be performed on a workpiece by the
25 movable tool.

3. The machine tool of Claim 2 characterized in that at least one of the objects comprises a model of a movable tool for shaping a workpiece, and the movable tool object exchanges messages with the shaping process object.

30 4. The machine tool of Claim 1 characterized by first and second objects each comprising a model of a shaping process to be performed on a workpiece, and the model of the second object is inherited from the first object.

35 5. The machine tool of Claim 1 characterized in that at least one of said objects comprises a model of a hole-making capable of forming a hole in a workpiece, the

model including definitions of the X, Y and Z dimensions of the hole.

6. The machine tool of Claim 1 characterized in that at least one of said objects comprises a model of a milling process capable of being formed in a workpiece, the model including a two-dimensional definition of a shape.

7. The machine tool of Claim 1 characterized in that at least one of said objects comprises a model of a contouring process capable of being performed on a workpiece being turned in a lathe.

8. The machine tool of Claim 1 characterized in that the objects include status means representative of whether the process defined by the object has been performed on a workpiece.

9. The machine tool of Claim 1 characterized in that at least one of the objects comprises a model of a movable tool for use in connection with shaping a workpiece.

10. The machine tool of Claim 1 characterized by means for receiving from movable tools signals indicating faults with a movable tool, and a device fault software module comprising means for storing information regarding detected faults from movable tools, means for storing, for each detected fault, a sublist of the objects to which to send an object oriented message identifying the detected fault, and means for sending, upon receiving information regarding a movable tool fault, an object oriented message to each object associated with the fault.

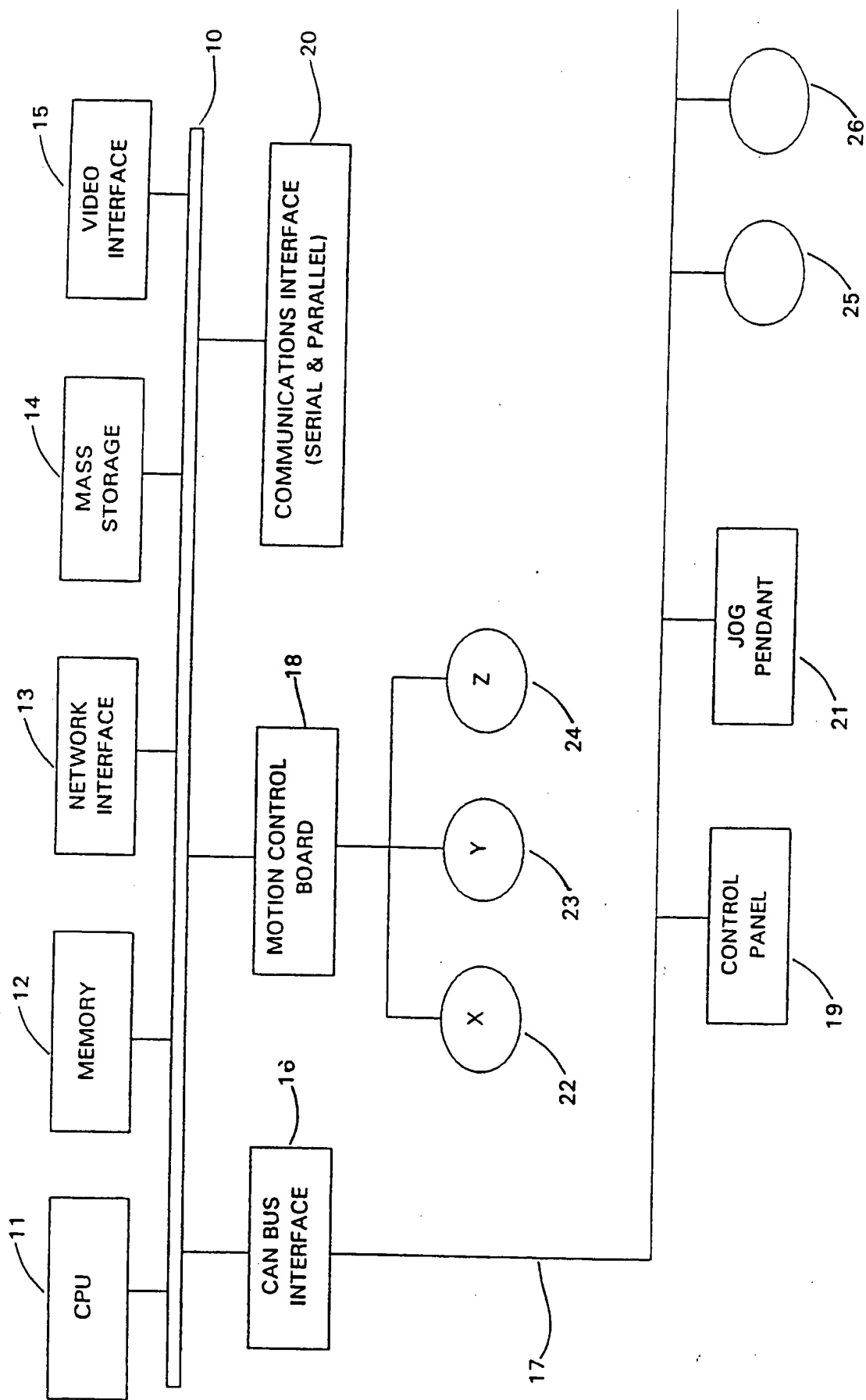


FIG. 1

2/2

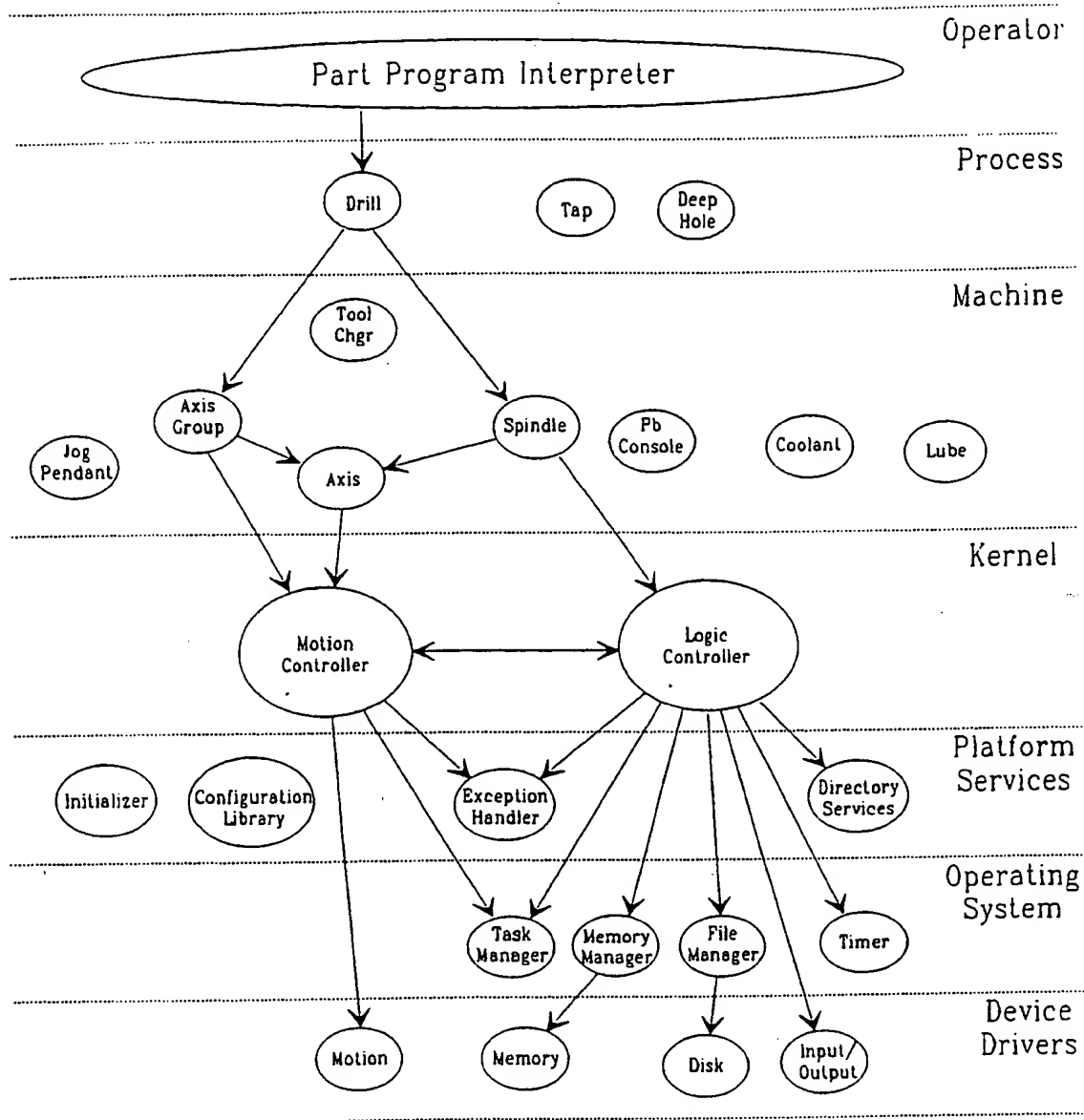


Fig.2

INTERNATIONAL SEARCH REPORT

International Application No.
PCT/US 94/10029

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G05B19/414

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6 G05B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	CONFERENCE RECORD OF 1991 43RD ANNUAL CONFERENCE OF ELECTRICAL ENGINEERING PROBLEMS IN THE RUBBER AND PLASTICS INDUSTRIES, 15 & 16 APRIL 1991, AKRON, OHIO, USA pages 58 - 68, XP299128 DAVID E. HALPERT 'Object Oriented Programming for Motion Control' see page 58 - page 68 ---	1-10
Y	VDI ZEITSCHRIFT, vol.135, no.5, May 1993, DUSSELDORF DE pages 73 - 78, XP303852 H.K. TÖNSHOFF, S. HAMELMANN & F.N. RUDOLPH 'Elementorientierte Konstruktion und Arbeitsplanung' see page 73 - page 78 --- -/--	1-10

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents :

- *A* document defining the general state of the art which is not considered to be of particular relevance
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Date of the actual completion of the international search

11 January 1995

Date of mailing of the international search report

19.01.95

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INTERNATIONAL SEARCH REPORT

Intern al Application No
PCT/US 94/10029

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	VDI ZEITSCHRIFT, vol.132, no.12, December 1990, DUSSELDORF DE pages 56 - 65, XP176612 H. SEIFERT & L. DRISIS 'Eine Benutzeroberfläche für den Objektprozessor' see page 56 - page 65 ---	1
A	COMPUTER NETWORKS AND ISDN SYSTEMS, vol.21, no.5, July 1991, AMSTERDAM NL pages 357 - 380, XP215758 M. BRILL & U. GRAMM 'MMS : MAP application services for the manufacturing industry' see page 357 - page 380 ---	1
A	VDI ZEITSCHRIFT, vol.135, no.1/2, January 1993, DUSSELDORF DE pages 73 - 78 H.K. TÖNSHOFF & C. HOLLEMAN 'Objektorientiertes Ressourcendatenmanagement auf Basis aktiver, dynamischer Sachmerkmaleisten' see page 73 - page 78 ---	1
A	FR,A,2 357 943 (HURCO MANUFACTURING COMPANY INC.) 3 February 1978 cited in the application see the whole document -----	1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/US 94/10029

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FR-A-2357943	03-02-78	CA-A- 1102434	02-06-81
		CH-A- 618528	31-07-80
		DE-A- 2730335	12-01-78
		GB-A- 1584646	18-02-81
		GB-A- 1584647	18-02-81
		GB-A- 1584645	18-02-81
		JP-C- 1375124	22-04-87
		JP-A- 53006784	21-01-78
		JP-B- 61042289	20-09-86
		JP-C- 1649006	13-03-92
		JP-A- 60186907	24-09-85
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		US-A- 4477754	16-10-84

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